CURRENT STUDIES IN TECHNOLOGY, ENGINEERING AND SCIENCES

EDITORS
Fatma Zerrin SALTAN
Huseyin ARIKAN
Yusuf UZUN

ISRES Publishing

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Current Studies in Technology, Engineering and Science

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Preface

Dear Readers,

The fields of science, engineering, and technology demonstrate constant progress and innovation in pushing humankind's limits. This work, titled "Current Studies in Technology, Engineering and Science", brings together the most current studies, research, and discoveries in these fields.

Today, research conducted in a wide range from basic sciences to engineering and technology aims to find solutions to the challenges faced by humanity. This book includes studies presented by distinguished researchers in a wide range of fields, from physics to biology, from chemistry to computer science. Each article and chapter aims to provide the reader with in-depth information on the subject.

The content of the book focuses on the challenges, innovations, and discoveries faced by scientists and engineers. In this way, we believe that our readers will not only update their current knowledge but also gain a perspective on the technological and scientific trends of the future.

While preparing this work, we brought together many valuable pieces of content that are the product of intense collaboration between editors and authors. We believe that these studies will foster progress in academia and industry.

Finally, we hope that this book, "Current Studies in Technology, Engineering and Science", will increase your interest in the fields of science, engineering, and technology and enable you to gain more in-depth knowledge of these subjects.

We wish you a good reading.

December, 2025

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In This Book

Chapter 1:

This study examines the critical role of information technologies in enhancing the accessibility and effectiveness of disaster management for individuals with disabilities. Natural disasters, particularly sudden-onset events like floods, disproportionately endanger this population due to persistent barriers in physical accessibility, communication, and inclusive planning within traditional emergency response systems. Through a comprehensive literature review and analysis, the chapter highlights how tailored technological solutions such as accessible early warning systems (e.g., multimodal alerts via mobile apps and wearable devices), GPS-based tracking tools, personalized disaster preparedness applications leveraging artificial intelligence, and digital platforms for post-disaster support and social integration can significantly mitigate these risks. However, the full potential of these technologies is constrained by challenges, including inadequate design standards, a lack of user training, high costs, infrastructural limitations, and privacy concerns. The study concludes that overcoming these barriers requires collaborative efforts among governments, technology developers, and civil society to promote inclusive design, expand accessibility standards, and raise public awareness. Ultimately, the strategic integration of information technologies is essential not only for safeguarding individuals with disabilities during disasters but also for fostering their active participation in disaster management processes and broader societal resilience.

Chapter 2:

This chapter provides a comprehensive review of the electromagnetic interference (EMI) shielding performance of carbon fiber reinforced polymer (CFRP) composites for aerospace structural applications. It outlines the fundamental mechanisms of EMI shielding—reflection, absorption, and multiple reflections—and discusses key parameters such as shielding effectiveness (SE) and specific shielding effectiveness (SSE) in relation to lightweight design requirements. The chapter systematically classifies CFRP-based shielding materials, including neat, metal-coated, conductive polymer-modified, carbon-based, MXene-based, and hybrid composites, highlighting their electromagnetic behavior and aerospace relevance. By correlating material design strategies with structural and electromagnetic performance, this chapter offers critical insights for the development of next-generation multifunctional CFRP composites for aircraft and space systems.

Chapter 3:

This chapter provides a comprehensive overview of swarm drone systems as a scalable and resilient autonomy paradigm in which multiple UAVs coordinate through local interactions and distributed decision-making to produce emergent collective behavior inspired by natural swarms. It connects key theoretical foundations in multi-agent coordination and consensus with the practical engineering stack required for real-world deployment, covering centralized, decentralized, and hybrid architectures; communication and networking considerations for reliable coordination; and robust sensing and positioning options that support operation in GPS-denied conditions through vision-based estimation and sensor fusion. Core autonomy capabilities are reviewed across formation control, task allocation and planning (including optimization- and learning-based approaches), on-board (edge) intelligence, and energy-aware operation, alongside representative software and hardware ecosystems used in practice. The chapter also examines safety, cybersecurity, and regulatory constraints together with major application domains such as disaster response, agriculture, inspection, and aerial light shows, concluding that dependable large-scale swarms require integrated progress across algorithms, edge intelligence, and maturing regulatory and ethical frameworks.

Chapter 4:

This chapter examines the critical role of quality control in the apparel industry with a specific focus on printing and embroidery processes. The study begins by emphasizing the apparel sector's global and national economic significance, particularly highlighting Turkey's competitive advantages. It then discusses how quality directly affects customer satisfaction, brand reputation, and production efficiency. Detailed sections describe major printing (such as water-based, pigment, and foil printing) and embroidery (such as flat, 3D, and satin stitch) techniques, along with their key quality determinants. The chapter identifies common defects—like stencil clogging, ink bleeding, misalignment, and oil stains—and analyzes their root causes. Finally, it explores modern quality control approaches, including automation, image processing, and artificial intelligence, which enhance defect detection and process consistency, marking a transition from traditional visual inspection to data-driven quality management. We would like to express our sincere gratitude to the management and personnel of *Beybo Boya Sanayi A.Ş.* for their valuable support and the opportunities provided during the fieldwork.

Chapter 7:

Surface engineering is a multidisciplinary field focused on modifying and improving the surface properties of materials to enhance their performance under demanding service conditions. Since most mechanical failures originate at the surface, surface engineering plays a crucial role in extending the lifetime and reliability of machine components exposed to friction, wear, corrosion, and high-temperature environments. Among advanced surface modification techniques, *Thermal Spray*, *Physical Vapor Deposition (PVD)*, *Chemical Vapor Deposition (CVD)*, and *Sol-Gel* processes have become prominent due to their ability to produce coatings with tailored microstructures and superior mechanical and chemical characteristics. Thermal spray coatings provide thick, wear-resistant layers suitable for heavy-duty applications, while PVD and CVD techniques offer dense and adherent thin films ideal for cutting tools and precision components. The sol-gel method, on the other hand, enables the formation of nanostructured oxide coatings at relatively low temperatures. This paper presents a comparative overview of these technologies, emphasizing their mechanisms, coating properties, and industrial applications, with particular focus on mitigating wear and extending the operational life of machine elements.

Chapter 8:

This study provides a comprehensive overview of robotics and artificial intelligence (AI), highlighting the development of robotic systems and fundamental AI concepts, including machine learning, natural language processing, decision-making, computer vision, and automated planning. It discusses automation in robotics, including system definitions, levels of automation, and technical and operational challenges. Recent advancements in AI-enabled autonomous robots are examined across various domains, such as autonomous vehicles, medical robotics, industrial automation, humanoid robots, and agricultural robotics. AI has significantly transformed professional environments and everyday life, with autonomous systems increasingly playing a central role in maritime operations, space exploration, aviation, field and terrestrial robotics, and service robotics. These systems enhance productivity, perform repetitive tasks, and improve operational quality. Robotic process automation (RPA) further optimizes workflows, enabling more efficient task execution across industries.

The importance of AI and robotics has grown notably since the Fourth Industrial Revolution and the advent of Industry 4.0, which aimed to reduce human labor dependency while developing autonomous systems capable of performing complex tasks efficiently. These technologies have also been rapidly adopted in sectors such as tourism and hospitality, enhancing customer experiences and transforming management and marketing strategies. Service robots in hospitality, for example, support front office operations, room service, and housekeeping, thereby improving service quality. In industrial contexts, robotics and automation enhance efficiency and competitiveness by reducing costs, ensuring high-quality production, and supporting technology transfer and high-tech investments in developing countries. Automation delivers consistent and precise operations that are difficult to achieve manually, and the integration of AI-driven technologies has reshaped industrial and business practices globally. Consequently, many countries have established national strategies and dedicated programs to promote innovation and advance the development of AI and robotic technologies.

Chapter 9:

This study presents the numerical determination and experimental verification of process windows for the Hydromechanical Deep Drawing (HMDD) process of a conical part made from AISI 304 stainless steel. The primary objective was to establish the safe operating limits for the two most critical parameters, fluid pressure and blank holder force (BHF), to prevent wrinkling and fracture defects. Separate process windows for each parameter were constructed as a function of punch position through an extensive series of Finite Element Analysis (FEA) simulations. The accuracy of these numerically derived windows was rigorously validated by a series of HMDD experiments designed to probe their boundaries. Experiments deliberately using loading profiles within the predicted wrinkling and fracture regions consistently resulted in the corresponding defects, while profiles within the safe zone successfully produced flawless parts. A key finding is that the safe zone for fluid pressure is significantly narrower than for BHF, highlighting the critical need for its precise control in industrial applications. The results conclusively demonstrate that the proposed FEA-based methodology can reliably generate accurate process windows, serving as a valuable know-how tool for optimizing HMDD processes, reducing experimental costs, and ensuring robust production of complex parts.

Chapter 10:

This study investigates the influence of high-pressure die casting (HPDC) process parameters on the mechanical properties and microstructure of A356 (AlSi7Mg) aluminum alloy, focusing on the feasibility of producing an automotive stabilizer bar. Three key parameters—temperature, injection velocity, and intensification pressure —were evaluated at three levels using a Taguchi L9 experimental design. Tensile specimens produced under nine different process conditions were tested with five repetitions each, and yield strength and plastic strain were analyzed.

The results demonstrated that pressure was the only statistically significant parameter affecting yield strength, accounting for approximately 73% of its variation according to ANOVA ($p < 0.05$). The highest mechanical performance—characterized by increased yield strength, tensile strength, and ductility—was obtained at 740°C, 2 m/s, and 1290 bar. The lowest performance occurred under the lowest temperature, lowest speed, and lowest pressure conditions. Plastic strain values ranged from 1.15% to 3%, indicating that high pressure, high temperature, and low velocity enhance the plastic deformation capability of the alloy.

Microstructural analysis revealed similar grain size and secondary phase morphology across all experiments, suggesting that the selected parameter range did not significantly alter the microstructure. However, the presence of porosity typical of HPDC contributed to brittle fracture behavior and variability in ductility between replicates.

Overall, the study concludes that optimizing pressure, in combination with high temperature and low injection speed, improves the mechanical performance of A356 alloy components produced by HPDC, providing a foundation for future process optimization in automotive applications.

Chapter 11:

Biomass stands out among renewable energy sources due to its unique characteristics. It has the potential to be the best alternative to fossil fuels. Biomass must be efficiently converted into energy. Various conversion techniques are used for this purpose. This study examines the work done on biomass conversion techniques over the last five years and evaluates the developments in this work. The findings of this study show that this field is constantly evolving, with new and innovative methods replacing traditional conversion technologies. Among these innovations, the use of nanofluids, hybrid techniques, and techniques utilising various materials, including nanomaterials as catalysts, have been observed. Furthermore, it has been assessed that pre-treatment techniques may also be effective in converting biomass into energy.

Chapter 12:

Lupinus L. (Fabaceae fam.), commonly known as lupin or “termiye,” is a plant whose seeds are traditionally consumed as food, particularly in the Konya region and coastal areas of Türkiye. Despite their high protein and fiber content, Lupinus species cultivated in Türkiye are recommended to be consumed with caution by both humans and animals due to the presence of anti-nutritional compounds (quinolizidine alkaloids) and high manganese levels. This chapter provides a comprehensive review of the botanical characteristics, ethnobotanical uses, phytochemical composition, and biological activities of wild and cultivated Lupinus species growing in Türkiye.

Lupinus species are rich in proteins, essential amino acids, alkaloids, flavonoids, phenolic acids, and bioactive peptides and exhibit a broad range of pharmacological activities, including antioxidant, anti-inflammatory, antidiabetic, antihypertensive, antihyperlipidemic, anticancer, antiparasitic, and immunomodulatory effects. However, some species contain high levels of alkaloids, which may lead to toxicity if not properly processed; therefore, debittering procedures are essential for food safety.

Studies on the phytochemical and biological profiles of Turkish Lupinus species remains limited. Comprehensive clinical investigations must be conducted on all species of Lupinus cultivated in Türkiye, with a particular emphasis on those consumed in powder form by vegans. It is vital to increase public awareness of their safe use and expand the cultivation of local Lupinus genotypes. Interdisciplinary research focusing on these species will help uncover their therapeutic potential, enhance their biotechnological applications, and contribute to the effective utilization of Türkiye’s rich medicinal plant diversity.

Chapter 13:

The behaviour of aluminium within cement-based systems is systematically examined, particularly with regard to the chemical and electrochemical interactions that occur in the high-alkalinity environment of ordinary Portland cement. The dissolution processes resulting from the destabilisation of aluminium's natural passive oxide layer due to the high pH conditions in concrete's pore solution are examined in detail. These processes include the formation of hydrogen gas and the impact of corrosion products with volumetric expansion on the concrete matrix. Electrochemical stability is evaluated using Pourbaix diagrams and an analysis of galvanic interactions explains the accelerated corrosion mechanisms that occur when aluminium comes into contact with steel reinforcement and anchorage elements. The chapter also compares international standards and design guidelines related to the use of aluminium in concrete (ACI, Eurocode 9, and Concrete Society), summarising the engineering requirements based on coating, electrical insulation, and chloride limitations specified in these documents. Furthermore, current structural and sustainable applications are touched upon, such as approaches to reducing pore solution alkalinity through mineral admixtures and alternative binder systems, as well as concrete-filled aluminium tubes and the controlled use of aluminium waste. Finally, future research directions are outlined in terms of material design, surface protection strategies, and galvanic isolation principles for the safe and long-term integration of aluminum into cement-based systems.

Chapter 14:

The microscope ranks among the most important inventions in the history of science, its discovery leading to the birth and development of numerous scientific disciplines. After the light microscope was developed, it was used for a long time for curiosity and entertainment purposes. However, the microscope later became an indispensable instrument used for scientific purposes, particularly in the fields of biology and medicine, where it is utilised clinically. With the help of microscopes, a scientific 'Cell Theory' was developed, and under the influence of this theory, the scientific fields of Histology and Embryology were born and developed. As can be seen, Histology and Embryology are among the scientific disciplines that owe their existence to the microscope. During this process, many new microscopic techniques for examining tissues under the microscope found their place. In parallel, new types of microscopes were developed, primarily the electron microscope. This section focuses on the development of the scientific fields of Histology and Embryology in light of the use of microscopes. In this way, the impact of microscopes on the scientific world is evaluated against a historical background, and the effects of this impact on both the present and the future are interpreted through the lens of the disciplines of Histology and Embryology.

Chapter 16:

High rates of exercise non-adherence and program dropout observed following the acute phase of physiotherapy rehabilitation constitute one of the most significant challenges threatening the long-term sustainability of achieved clinical gains. Addressing this pervasive issue requires a sophisticated, multi-modal strategy rooted in modern behavioral science and precision mechanics.

This book chapter aims to examine contemporary, evidence-based approaches to ensure exercise sustainability in physiotherapy, specifically utilizing the Biopsychosocial (BPS) Model framework which integrates biomechanical precision, behavioral sciences, and technological integration. The discussion begins by establishing the physiological and neurobiological foundations of sustainability, stressing the critical role of Graded Exposure (GE) strategies in disrupting the Kinesiophobia (fear of movement) and the Fear-Avoidance Cycle, recognized as the central psychological component of chronic pain.

Furthermore, the chapter meticulously details how Optimal Loading Dosage must be precisely individualized based on the distinct healing kinetics of various tissues (including muscle, tendon, and bone) to maximize necessary tissue adaptation while simultaneously minimizing the risk of recurrent injury (Gabbett & Oetter, 2025). Within the scope of patient-centered approaches, the text recommends the strategic setting of SMART (Specific, Measurable, Achievable, Relevant, Time-bound) goals to enhance Self-Efficacy, which is the single most powerful psychological predictor of successful exercise adherence.

The psychosocial pillar of therapy is supported by integrating principles of Cognitive Behavioral Therapy (CBT), particularly cognitive restructuring aimed at challenging and modifying Catastrophizing behavior , and utilizing Motivational Interviewing (MI) techniques, which play a pivotal role in strengthening the patient’s intrinsic desire for change. Finally, the environmental component necessary for sustained compliance is achieved through the integration of Tele-Rehabilitation, mobile applications, and Objective Feedback provided by Wearable Technologies, which collectively support remote monitoring and reinforce patient autonomy over the long term.In conclusion, the role of the physiotherapist is fundamentally being redefined as a behavioral coach. Future success in this domain is projected to be secured through the integration of artificial intelligence-based personalized treatment algorithms and the formal incorporation of behavioral sciences into core physiotherapy curricula.

Accessible Disaster Management: Information-Based Solutions for Individuals with Disabilities

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Introduction

In recent years, due to climate change and environmental factors, the frequency and severity of natural disasters have increased significantly worldwide. Disasters such as earthquakes, hurricanes, wildfires, and floods cause significant loss of life and property, leaving a profound impact on societies. Floods, in particular, pose significant risks due to their sudden onset and their capacity to affect large areas. These disasters, caused by heavy rainfall, dam overflows, or rivers breaking through floodplains, can inundate residential areas, damage critical infrastructure, and pose a serious threat to human life.

Floods are not limited to physical destruction; they also cause economic, social, and psychological impacts. The inundation of agricultural lands, damage to infrastructure, and destruction of homes lead to long-term economic hardship. This can be particularly devastating for vulnerable communities and disadvantaged groups, such as individuals with disabilities. Individuals with disabilities often face greater challenges than others during disasters. Factors such as accessibility issues, communication barriers, and the inability to participate in disaster response processes jeopardize the safety of these individuals.

In this context, the importance of information technologies is increasingly recognized for mitigating the impacts of natural disasters, especially floods, on individuals with disabilities and increasing their resilience to disasters. By offering a wide range of solutions, from early warning systems to accessible communication tools, information technologies can help protect individuals with disabilities in disaster management processes and ensure their social integration.

When natural disasters strike a community unexpectedly, they create significant challenges for all individuals. However, these challenges can be even more complex and devastating for individuals with disabilities. Individuals with visual, hearing, mobility, or cognitive impairments face significantly greater risks than others in disaster situations. Factors such as accessibility issues, communication barriers, and the inability to participate in emergency response processes seriously threaten the safety of these individuals.

Individuals with disabilities are often placed closer to danger during disasters. For example, due to physical disabilities, they may have difficulty exiting a building in a situation requiring rapid evacuation, or visually impaired individuals may struggle to understand complex emergency signs and instructions. Individuals with hearing impairments may not receive emergency alerts and instructions promptly, making them more vulnerable to danger. Furthermore, individuals with cognitive disabilities may struggle to understand the complexities of disaster situations, which can hinder their ability to navigate safely.

Disaster response processes also present significant accessibility challenges for individuals with disabilities. Emergency evacuation plans often fail to adequately consider the specific needs of individuals with disabilities. Communication tools and information systems used in disaster areas are often unsuitable for individuals with disabilities. For example, audio warnings are ineffective for a hearing-impaired individual, while visual signals are useless for a visually impaired individual. This restricts individuals with disabilities' access to vital information during emergencies, placing them at greater risk.

Information technologies can play a vital role in overcoming these challenges and increasing the resilience of individuals with disabilities to disasters. Solutions such as accessible early warning systems, specialized evacuation plans for individuals with disabilities, and post-disaster support services are essential to better protect these individuals in disaster situations and strengthen their social integration.

Although natural disasters are devastating events that affect all segments of society, individuals with disabilities face greater risks in such situations. Accessibility issues, communication barriers, and difficulties in participating in emergency response processes seriously jeopardize their safety. However, the innovations and solutions offered by modern information technologies can play a significant role in overcoming these challenges.

Information technologies have the potential to revolutionize disaster management and response processes. Information technology solutions specifically designed to meet the needs of individuals with disabilities can facilitate their access to vital information and services during disasters. For example, technologies such as mobile applications that provide audio notifications for visually impaired individuals, visual and text-based early warning systems for hearing impaired individuals, and location-based emergency assistance requests for individuals with mobility impairments can be quickly activated during disasters and prevent loss of life.

These technologies are critical for meeting the needs of individuals with disabilities, not only in emergencies but also in the post-disaster period. Providing accessible healthcare, shelter, and support services after a disaster can be achieved more effectively and quickly through information technology. This can help integrate individuals with disabilities into post-disaster recovery processes and increase social resilience.

The significance of this study lies in its evaluation of information technology solutions that will increase the resilience of individuals with disabilities against disasters and meet their needs in disaster management processes. Alleviating the challenges faced by individuals with disabilities during natural disasters and ensuring their full participation in society is not only a human rights issue but also a critical requirement for strengthening social solidarity and resilience. In this context, exploring and applying the potential offered by information technologies can provide great benefits at both individual and societal levels.

Literature Review

Obstacles Encountered in Disaster Management for Individuals with Disabilities

Evacuation plans in emergencies often fail to consider the needs of individuals with disabilities. For example, the inaccessibility of emergency exit routes for wheelchair users poses a significant obstacle in disaster situations. The design of buildings, the location of shelters, and the lack of disability-friendly emergency shelters make safe evacuation difficult. Warnings and information provided during disasters are often not tailored to the needs of individuals with disabilities. The lack of visual signals for individuals with hearing impairments and the inadequacy of audible warnings for individuals with visual impairments pose significant risks. Furthermore, individuals with cognitive disabilities can have difficulty understanding complex information.

Disaster management plans often overlook individuals with disabilities. If pre-disaster preparations are not structured appropriately for the specific needs of these individuals, effective response during a disaster is impossible. Mass evacuation plans, in particular, are inadequate to ensure the safe evacuation of individuals with disabilities. Personnel and volunteers working in disaster management processes often lack sufficient training in the needs of individuals with disabilities. This lack leads to inadequate support provided to these individuals during disasters.

Individuals with disabilities may face discrimination due to societal prejudices during disasters. These individuals may be overlooked or relegated to the background in post-disaster relief and reconstruction processes. In some communities, individuals with disabilities are marginalized in terms of social roles and duties. These cultural perceptions can make it difficult for disaster management plans to be inclusive of these individuals.

Studies on accessible disaster management focus specifically on how to make evacuation plans and warning systems more accessible to individuals with disabilities. This research emphasizes the need to adopt universal design principles in disaster management processes. For example, UNISDR (United Nations Office for Disaster Risk Reduction) and other international organizations have developed policy recommendations to reduce disaster risks and ensure the safety of individuals with disabilities. These recommendations encourage inclusive planning and the participation of individuals with disabilities in disaster management processes.

Studies on the development of early warning systems tailored to the needs of individuals with disabilities emphasize the importance of specialized technologies that will enable these individuals to be notified of disasters. For example, vibrating warning devices are being considered for individuals with hearing impairments, while systems equipped with audio signals are being considered for individuals with visual impairments. International conferences such as the Global Platform for Disaster Risk Reduction have presented recommendations for the development and dissemination of accessible communication tools. Such studies demonstrate the need to make communication technologies more inclusive.

Disaster education studies provide important information on how individuals with disabilities should prepare for disasters. These studies highlight the need to develop specialized training programs for individuals with disabilities and raise public awareness. For example, studies conducted by Japan’s Disability Information Resources indicate that disaster education for individuals with disabilities in Japan increases their resilience to disasters and enables them to actively participate in disaster management processes.

The Impact of Information Technologies on Accessibility

Information technologies can help individuals with disabilities overcome many physical and cognitive barriers. For example, screen readers enable visually impaired individuals to use computers and mobile devices; subtitling technologies enable access to media content for individuals with hearing impairments. Information technologies can be customized to meet users’ individual needs. For example, various solutions have been developed for individuals who struggle with keyboard and mouse use, such as alternative input devices, voice-activated systems, or technologies that can be controlled through eye movements.

Making digital content such as websites, mobile applications, and digital documents accessible significantly increases access to information for individuals with disabilities. Standards such as the Web Content Accessibility Guidelines (WCAG) have provided guidance in ensuring that digital content is accessible to individuals with disabilities. Information technologies make it easier for individuals with disabilities to maintain independent lives. For example, smart home technologies allow them to control their daily activities. Voice assistants enable individuals with disabilities to move more independently in the home environment (Anaç et al., 2010).

The use of information technologies in education has expanded the access of individuals with disabilities to educational opportunities. Online education platforms, in particular, enable the active participation of individuals with disabilities in the learning process. In the employment sector, information technologies support flexible working models that allow individuals with disabilities to work remotely. Social media and digital communication tools have increased the participation of individuals with disabilities in social life. These platforms allow individuals with disabilities to interact with communities and expand their social circles.

The literature emphasizes that information technologies should be developed in line with inclusive design principles. Inclusive design aims to ensure that everyone, especially individuals with disabilities, can use technology equally. Studies in this area argue that the needs of individuals with disabilities should be considered from the technology design stage onward.

Research examines the challenges individuals with disabilities face in using technology and the solutions developed to overcome these challenges. For example, it focuses on the factors that hinder the use of technology by individuals with disabilities. Research has revealed that the cost of access to technology, user training, and ease of use of devices are the primary factors affecting technology use (Kaye et al., 2008). The literature also includes studies on how information technologies support the social integration of individuals with disabilities. It is stated that social media and digital communication tools are effective in expanding the social networks of individuals with disabilities and reducing social isolation (D. Chadwick et al., 2013).

The use of technology in education has expanded the educational opportunities of individuals with disabilities. For example, it has been stated that online education platforms provide flexible and accessible learning environments for students with disabilities (Phipps, 2012). Similarly, it has been shown that digital tools used in education increase the participation of individuals with disabilities in the learning process. Information technologies have increased the accessibility of healthcare services for individuals with disabilities (Côté-Douyon, 2016). It has been stated that telehealth services facilitate access to healthcare services for individuals with disabilities and help them monitor their health status (Guo et al., 2005).

The role of information technologies in employment for individuals with disabilities also holds a significant place in the literature. It emphasizes that individuals with disabilities can increase their participation in the workforce by taking advantage of remote working opportunities thanks to information technologies. At the same time, adaptive technologies used in the workplace increase the job performance and productivity of individuals with disabilities (Kregel, 2008).

Although information technologies offer significant benefits, there are also studies indicating that not all individuals with disabilities have equal access to these technologies. They highlight the digital divide among individuals with disabilities. This divide stems from the high cost of technological devices, inadequate user training, and the inaccessibility of technology. Privacy and security concerns also play a significant role in the use of information technologies developed for individuals with disabilities (Mann et al., 2013). They discuss the challenges faced by individuals with disabilities regarding the protection and security of their personal information when using social media and digital platforms (D. D. Chadwick & Fullwood, 2018).

Early Warning Systems and Accessibility

For individuals with disabilities to effectively benefit from disaster warning systems, these systems must be accessible. Individuals with visual, hearing, motor, or cognitive disabilities each have different needs. Successful examples of systems developed to meet these needs can be found in the literature. It is emphasized that accessible early warning systems should offer multiple warning channels tailored to the needs of individuals with disabilities. For example, audible alerts are used for individuals with visual impairments, while vibrating or visual alerts are used for individuals with hearing impairments.

Many mobile applications make early warning systems accessible to individuals with disabilities. For example, applications developed by FEMA (Federal Emergency Management Agency) provide alerts tailored to users' individual needs. Wearable devices are also used in early warning systems. These devices can provide warnings with vibration, sound, or visual signals in the event of a disaster. Web-based platforms offer personalized alerts for individuals with disabilities. For example, CAP (Common Alerting Protocol) is used to provide customizable alerts for different disability groups (Yılmaz et al., 2014). Many studies argue that early warning systems should be developed in accordance with international accessibility standards. Standards such as WCAG (Web Content Accessibility Guidelines) play a critical role in ensuring that these systems are accessible to individuals with disabilities. The literature focuses on warning systems that can be customized to the individual needs of individuals with disabilities.

These systems can provide differentiated warnings based on the type of disaster, the individual's disability, and their geographic location. Various studies emphasize the need to test developed early warning systems based on user experience and feedback. This can increase the effectiveness of the systems and ensure better performance in real-world disaster scenarios (WAI Initiative, n.d.).

Developed in the US, the ShakeAlert system is an early warning system designed to improve the safety of individuals with disabilities during disasters. Developed specifically for earthquake warnings, this system provides accessible alerts across a variety of devices and platforms (ShakeAlert – Because seconds matter., n.d.). SIGN is a warning system specifically designed for individuals with disabilities during disaster management and can be customized to the needs of local communities and individuals. EENet is a platform that provides alerts tailored to different disability types, enabling faster and more effective response in the event of a disaster.

These studies and applications demonstrate how information technologies can be used in early warning systems for individuals with disabilities and how they play a role in increasing the effectiveness of these systems. Studies in this area contribute significantly to making disaster management processes more accessible.

The Effectiveness of Information Technologies

Information technologies offer systems designed to facilitate access to information for individuals with disabilities before, during, and after disasters. Early warning systems provide critical disaster information in formats suitable for individuals with disabilities (e.g., audio notifications for the visually impaired and visual alerts for the hearing impaired). This allows individuals to respond more quickly and effectively to disasters. Information technologies provide mobile applications tailored to the needs of individuals with disabilities, providing access to critical information during disasters. These applications can be customized to meet user needs and provide significant support in disaster management processes.

Information technologies allow individuals with disabilities to be tracked and identified during disasters. For example, GPS-based tracking systems can locate individuals with disabilities, allowing emergency responders to reach them more quickly. These systems also facilitate communication with family members and aid organizations. Virtualized rehabilitation programs can be used to help individuals with disabilities recover and reintegrate into society after a disaster. These programs provide physical therapy or psychological support, helping individuals recover more quickly from the adverse effects of the disaster.

Information technologies can be used to raise awareness about people with disabilities throughout society. Before and after disasters, awareness campaigns can be organized about the needs and rights of individuals with disabilities. These campaigns enable all members of society to be more sensitive and supportive of individuals with disabilities. Individuals with disabilities can engage in digital participation and social media through information technologies. These platforms allow them to have their voices heard, stay connected to their communities, and participate in disaster management processes. Social media is a particularly important tool for post-disaster support and solidarity.

Artificial intelligence and data analytics can be used to develop personalized disaster preparedness plans for individuals with disabilities. These systems can analyze individuals' needs and provide tailored solutions. For example, the types of assistance they will need during a disaster can be determined in advance, and plans can be made accordingly. Information technologies can create community-based support networks for individuals with disabilities. These networks facilitate mutual aid during and after a disaster and prevent individuals from feeling isolated. Furthermore, through these networks, community members gain information on how to support individuals with disabilities.

Information technologies can help policymakers and governments develop more accessible disaster management policies for individuals with disabilities. Data-based analyses and simulations can be used to assess the effectiveness of these policies. Information technologies support international collaboration and the development of standards to increase the resilience of individuals with disabilities to disasters. These standards can better protect individuals with disabilities worldwide in disaster situations.

Information technologies not only enhance the resilience of individuals with disabilities against disasters but also integrate them into society, allowing them to actively participate in disaster management processes. This plays a critical role in improving the overall well-being of both individuals and society.

Obstacles and Solutions

The design and implementation of information technologies are often optimized for standard user needs, which can lead to accessibility issues for individuals with disabilities. Designs should be developed in accordance with WCAG (Web Content Accessibility Guidelines) and other accessibility standards. User testing should be conducted during the design process, incorporating feedback from individuals with disabilities.

Existing technologies may not be sufficiently optimized for all types of disabilities. For example, some early warning systems may not be effective enough for individuals with hearing impairments. Technologies should be personalized and solutions tailored to different types of disabilities should be provided. For example, voice prompts should be used for individuals with visual impairments, while visual and vibration alerts should be used for individuals with hearing impairments. Investments should be made in accessibility research and technology development.

There may be a lack of sufficient knowledge and training on how to use information technologies for individuals with disabilities and the general public. Training programs on the use of accessible technologies should be organized for individuals with disabilities and disaster management personnel. Information campaigns should be conducted to explain the advantages of technologies and accessibility solutions.

The development and implementation of accessible technologies can be costly, and some regions may lack infrastructure. Government support and grants should be provided for the development and deployment of accessible technologies. Investments should be made to address infrastructure gaps and ensure technologies reach a wider audience.

Cultural and language barriers can make it difficult to effectively implement accessible technologies in some regions. Collaboration with local experts should be undertaken to adapt technologies to local cultures and languages. Multilingual support for accessibility solutions can facilitate use by individuals who speak different languages. The use of accessible technologies can raise security and privacy concerns, particularly regarding the protection of personal data. Strong data protection and encryption techniques should be used to ensure the security of user data. Users should be informed about how their data is collected and used.

Access to technology can be challenging, particularly in rural and low-income areas. Affordable and accessible solutions should be provided to make technology accessible to a wider audience. Public-private partnerships should be encouraged to disseminate technology and increase access points. Overcoming these barriers will make information technologies more effective and accessible for individuals with disabilities, leading to significant advances in disaster management processes.

Conclusion

This study examined the challenges faced by individuals with disabilities during natural disasters and the potential role of information technologies in overcoming these challenges. Natural disasters, particularly emergencies such as floods, pose greater risks to individuals with disabilities and increase their safety risks. Traditional disaster management systems and response processes fail to adequately meet the needs of individuals with disabilities and have significant accessibility gaps. Information technologies offer significant opportunities to address these shortcomings.

Information technologies can transform disaster management processes through early warning systems, post-disaster support services, and accessible communication tools developed for individuals with disabilities. Artificial intelligence-based applications, in particular, can create personalized disaster preparedness and response plans, increasing the resilience of individuals with disabilities to disasters. Furthermore, social integration processes are supported through mobile applications and digital platforms, ensuring the participation of individuals with disabilities in society.

However, several barriers must be overcome for information technologies to be fully integrated into the lives of individuals with disabilities. Challenges such as accessibility issues, educational deficiencies, and financial constraints limit the effective use of these technologies. To overcome these obstacles, governments, civil society organizations, and technology developers must work collaboratively. Strengthening technological infrastructure, expanding accessibility standards, and raising public awareness will enable individuals with disabilities to take a more active role in disaster management processes.

Consequently, the use of information technologies is critical for individuals with disabilities to become more resilient to disasters and to access the support they need during disasters. Making these technologies more accessible to a wider audience will contribute to the stronger participation of individuals with disabilities not only in disaster management but also in all aspects of social life. New policies and technological solutions will help ensure greater safety and social integration for individuals with disabilities in the face of disasters.

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Electromagnetic Shielding Performance of Carbon Fiber Reinforced Polymer Composites for Aerospace Structural Applications

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Introduction

The aerospace industry is a multidisciplinary field that involves designing, manufacturing, and operating aircraft and spacecraft. It is characterized by strict requirements for high performance, reliability, and safety. Systems and components used in this sector must demonstrate high structural accuracy and electronic stability to ensure consistent and safe operation (Parveez et al., 2022; Siengchin, 2023). Materials used in aerospace applications need to withstand harsh environmental conditions encountered during flight, such as high temperatures, pressure changes, vibration, radiation, and rapid thermal shifts. Given the demands of long-duration missions and high-speed operations, material properties like low density, mechanical strength, and thermal stability are critically important. In addition to engineering factors, considerations such as cost, availability, and maintainability also play a key role in selecting suitable materials for aerospace structures (Xia, 2023).

Within this context, materials used in aerospace structures are chosen by balancing their strength, density, temperature resistance, and manufacturability. Traditionally, aluminium, titanium, and steel alloys have been the main engineering materials in aircraft and spacecraft construction. Aluminium alloys, due to low density, excellent formability, and high specific strength, are commonly employed in fuselage panels, wings, and outer skins. Titanium alloys, characterized by a superior strength-to-weight ratio and resistance to corrosion and high temperatures, are preferred for engine components, landing gear parts, and critical joints. Steel, on the other hand, is mainly employed in load-bearing components and structural connectors that require exceptional hardness and fatigue resistance. However, these traditional metallic materials also have inherent limitations, including susceptibility to corrosion, high density, and high production costs (Hirankittiwong et al., 2025). Therefore, the search for lightweight, durable, and multifunctional alternatives has gained momentum in recent years.

Driven by goals such as weight loss, fuel efficiency, and performance improvement, carbon fiber reinforced polymer (CFRP) composites have become advanced materials for modern aerospace and space platforms. CFRP composites are lightweight, structurally efficient materials that deliver excellent mechanical properties, including high strength, fatigue resistance, and low density (Hamzat et al., 2025). Because of these benefits, CFRPs provide higher specific performance than traditional metallic structures and are increasingly used in aerospace engineering. Blends of carbon, glass, or aramid fibers embedded in polymer matrices offer notable strength, corrosion resistance, design flexibility, and weight savings. In particular, continuous carbon fiber reinforced composites are commonly used in key structural parts, such as fuselage panels, wings, tail sections, and satellite components (Hirankittiwong et al., 2025; Maria, 2013). Additionally, the natural electrical conductivity of carbon fibers allows CFRP composites to provide electromagnetic interference (EMI) shielding, improving the reliability of avionics, radar, and communication systems. As a result, CFRPs are viewed as multifunctional materials that combine high mechanical performance with electromagnetic protection in today's aerospace structures (W. Dong et al., 2025).

The rapid advancements in nanotechnology and digital communication—especially the widespread adoption of 5G networks—have further integrated electronic systems into aerospace structures. Modern aircraft and spacecraft feature numerous electronic devices, including radar systems, communication modules, power lines, and precision sensors (Prekodravac Filipovic et al., 2025). During operation, these devices emit electromagnetic waves (EMW), which contribute to EMI and radiation pollution. The increasing density of EM sources threatens the stability and reliability of aerospace systems, especially in high-frequency communication environments (X. Y. Wang et al., 2022). Therefore, the use of high-performance electromagnetic shielding (EM-shielding) materials has become essential. Thanks to their light weight, high mechanical strength, and design flexibility, CFRP-based composite materials offer an ideal solution for meeting both structural and EMI protection needs. CFRP composites with wide effective absorption bandwidths (EAB), high absorption capacity, and thin matching thicknesses not only ensure the reliable operation of onboard electronics but also help protect human operators from the harmful effects of electromagnetic radiation (Suresha et al., 2024).

The main goal of this study is to thoroughly evaluate the electromagnetic shielding effectiveness (EMSE) of CFRP composites used in aerospace structures. It also evaluates the mechanical and environmental performance of these materials and examines their EMI shielding capabilities, providing insights for the development of next-generation multifunctional composites.

1.Fundamentals Of EMI Shielding

This section presents a comprehensive overview of the fundamental principles governing electromagnetic interference (EMI) shielding in advanced composite materials. It begins by introducing the essential characteristics of electromagnetic waves and describing their interaction with matter through reflection, absorption, and transmission phenomena. The discussion then addresses the physical mechanisms that determine shielding effectiveness, highlighting the parameters that influence electromagnetic attenuation in CFRP composites. Particular emphasis is placed on experimental evaluation approaches—such as EMI shielding measurements and analytical calculations—that enable the quantitative assessment of material performance. Furthermore, the dielectric and magnetic behaviours of the composites are analysed to elucidate their contributions to energy storage, dissipation, and loss mechanisms. Collectively, these discussions establish the theoretical and experimental foundation required to understand and optimize the EMI shielding performance of CFRP composites employed in aerospace structural systems.

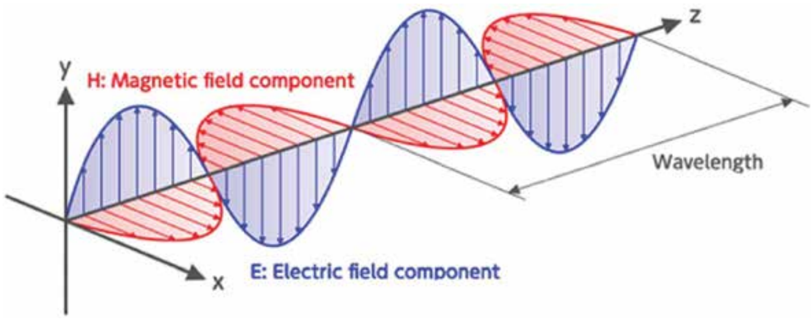
1.1.Electromagnetic Waves

Electromagnetic waves are transverse waves that transmit energy, resulting from the oscillation of magnetic and electric fields in mutually perpendicular planes. These waves are generated by the simultaneous interaction of magnetic and electric fields and can travel through a vacuum at the speed of light without requiring a physical medium, as shown in Figure 1 (Kruželák et al., 2021). The primary sources of electromagnetic wave production are the acceleration of charged particles or changes in their energy states. Electromagnetic waves display both wave-like and particle-like characteristics; therefore, energy can be transferred either as a continuous wave or as discrete packets called photons (Wdowiak et al., 2017).

The wave impedance describes the ratio between the magnitudes of the electric and magnetic fields, determining how energy is transmitted through the propagation medium. In free space, the intrinsic impedance is about 377 Ω, representing the characteristic impedance of the two fields (Rouhi et al., 2022). Far from the source, the wave shows typical behavior in the far-field region. Near the source, complex interactions among different field components create the near-field region. Based on their wavelength and frequency, electromagnetic waves are classified within the electromagnetic spectrum, which ranges from radio waves and microwaves to infrared, visible light, ultraviolet, X-rays, and gamma rays. Although electromagnetic waves do not lose energy as they propagate through space, they can undergo reflection, absorption, or conversion to other forms when interacting with matter (Zheng, Wang, Wang, et al., 2024).

Figure 1

Schematic Illustration of an Electromagnetic Wave

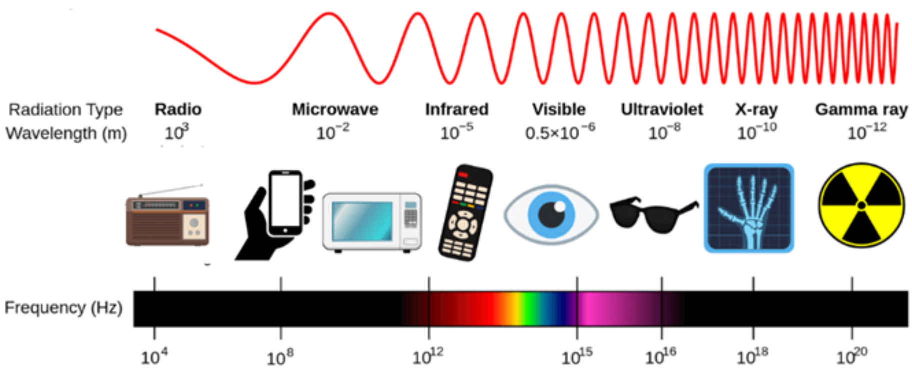


1.2.Electromagnetic Spectrum

The electromagnetic spectrum covers a wide range of frequencies—from radio waves to gamma rays—each region exhibiting distinct energy levels and interaction characteristics depending on its wavelength and frequency (Dungani Rudi et al., 2018). These frequency differences are vital for assessing EMI risk, especially in electronic and communication systems. As illustrated in Figure 2, Low-frequency radio waves can cause long-distance interference, while high-frequency microwave and terahertz waves produce short-range but more powerful interference effects. Therefore, the effectiveness of EMI shielding depends strongly on selecting materials and design strategies that correspond to the target frequency band. For instance, thin metallic layers or conductive polymer composites are commonly employed for shielding high-frequency electromagnetic waves, while thicker conductive or magnetic materials are more suitable for mitigating low-frequency interference (Mishra et al., 2018). As a result, understanding the distribution of frequencies across the electromagnetic spectrum is essential for selecting proper materials and designing structures in EMI shielding applications.

Figure 2

Electromagnetic Spectrum

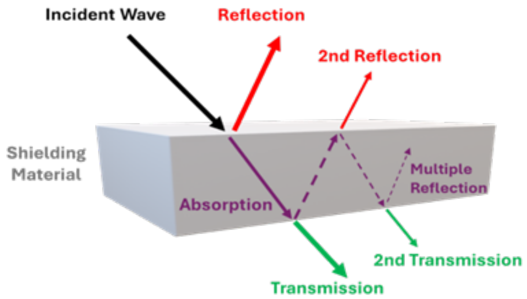


1.3.Mechanism of EMI Shielding

EMI shielding involves reducing the transmission of electromagnetic waves through space by using suitable shielding materials, thus protecting objects from incident radiation (Mishra et al., 2018).To explain the shielding performance observed in experimental studies, researchers have proposed several theoretical approaches, including electromagnetic field theory, eddy-current theory, and transmission line theory. Among these, transmission line theory has been widely accepted due to its computational simplicity, physical clarity, and high predictive accuracy (Hlo, 2021). According to this theory, when an electromagnetic wave interacts with a shielding material, three main mechanisms—reflection, absorption, and multiple reflections—contribute to its overall effectiveness. These mechanisms form the core principles of EMI shielding design and offer a critical framework for understanding how material choice, layer thickness, and structural configuration impact shielding performance (Tian et al., 2023).

Figure 3

Schematic Illustration of the EMI Shielding Mechanisms



1.3.1.Reflection

Reflection is a fundamental electromagnetic shielding mechanism in which a significant portion of incident electromagnetic energy is scattered back when waves strike a surface with high electrical conductivity. Free charge carriers on the surface—primarily electrons—interact with the electric-field component of the incoming wave, reflecting most of the electromagnetic energy outward (Hlo, 2021)

The effectiveness of reflection depends not only on the material's electrical conductivity but also on the impedance mismatch between adjacent media. The greater the impedance difference, the larger the fraction of energy reflected. Materials with high electrical conductivity enhance this mismatch and thereby strengthen reflection (Tian et al., 2023)

In this context, the percolation threshold is essential for understanding reflection behavior in composite systems. It represents the critical filler concentration at which conductive particles form continuous networks within the matrix. Once this threshold is exceeded, the material becomes macroscopically conductive, enabling efficient reflection of incident electromagnetic waves. As a result, composites designed above the percolation threshold show significantly better reflection-based shielding performance.

The degree of reflection is also influenced by the material's magnetic permeability (μ). As permeability approaches the vacuum value, resistance to wave propagation decreases; however, when permeability is low and conductivity is high, energy loss primarily occurs through reflection (Ismail & Azis, 2024). A combination of high conductivity and low permeability provides optimal reflection-dominated EMI protection. Therefore, aluminium alloys and conductive polymer composites—commonly used in aerospace structures—are ideal materials for reflection-based EMI shielding.

1.3.2.Absorption

Absorption is a dissipation mechanism in which incident electromagnetic waves penetrate a material and convert most of their energy into heat through electrical and/or magnetic losses. This process is associated with several physical phenomena, including the formation of conductive networks, dipole polarization, magnetic resonance, and eddy currents (Parvez et al., 2025).

To enhance absorption efficiency, materials are often reinforced with magnetic fillers such as Fe_3O_4, ferrites, Ni, and their alloys, along with electrically conductive nanofillers like MXene, carbon nanotubes (CNTs), and graphene. The thickness of the material also plays a crucial role: increasing thickness lengthens the wave's propagation path within the medium, thereby boosting energy attenuation (Yao et al., 2021). However, the optimal thickness must be selected carefully to ensure frequency and impedance matching; otherwise, surface reflections can become dominant, decreasing absorption efficiency.

The dielectric loss (ε'') and magnetic loss (μ'') components are the main factors that determine absorption performance. Therefore, structures that focus on absorption are usually designed as multiphase, micro- or nanoscale composite systems (Tian et al., 2023).

In aerospace applications, this mechanism is used to suppress radar waves, protect electronic components, and isolate signals. Specifically, Fe- and Ni-based alloys, along with CFRP composites, are suitable for applications that require both structural strength and electromagnetic performance.

1.3.3.Multiple Reflection

Multiple reflection is a secondary attenuation mechanism in which electromagnetic waves are repeatedly reflected and attenuated within a material through interactions with microscopic surfaces, pores, phase boundaries, or layered structures (Hlo, 2021). Although not the primary mechanism, it boosts overall EMI attenuation by increasing reflection- and absorption-related energy losses. Low-density, porous, or multiphase structures are especially effective in encouraging this behaviour, as the longer propagation path within the material allows the wave to lose more energy with each reflection.

Accordingly, the multiple-reflection effect increases with increasing material thickness; however, to ensure absorption remains dominant, the thickness must be optimized to prevent impedance-matching disruption (Yao et al., 2021)

In aerospace structural systems, this mechanism is often incorporated using micro- or mesoporous materials such as carbon foams, CNT networks, and MXene/ceramic hybrid layered composites. Thanks to their lightweight nature and high surface area, these materials both improve multiple reflections and provide mechanical stability under load.

1.4.EMI Shielding Effectiveness (EMI SE)

EMI shielding involves using engineered materials to reduce electromagnetic disturbances (EMD) and protect sensitive systems from external radiation. The effectiveness of these materials is usually measured by the electromagnetic shielding effectiveness (EMI SE) parameter, which indicates the amount of incident electromagnetic energy blocked, typically expressed in decibels (dB).

Theoretically, the EMI shielding efficiency of conductive materials can be estimated using the Simon formulation in Equation (1):

$$SE = 50 + \log\left(\frac{\sigma}{f}\right) + 1.7t\sqrt{\sigma f} \tag{1}$$

Where σ is the electrical conductivity (S•cm^{-1}), f is the frequency of the electromagnetic wave (MHz), and t is the thickness of the shielding layer (cm). This expression indicates that EMI SE increases with higher electrical conductivity and material thickness.

At a specific point relative to the radiation source, shielding effectiveness can also be expressed as Equation (2):

$$EMI\ SE = 10\ log\left(\frac{P_i}{P_t}\right) = 20\ log\left(\frac{E_i}{E_t}\right) = 20\ log\left(\frac{H_i}{H_t}\right) \tag{2}$$

Where P, E, and H represent the power, electric field strength, and magnetic field strength of plane waves, with subscripts i and t indicating incident and transmitted waves, respectively (Kruželák et al., 2021).

When an electromagnetic wave hits a shielding material, three main attenuation mechanisms happen:

(i) Reflection (SER) at the surface caused by impedance mismatch.

(ii) Absorption (SEA) within the bulk caused by ohmic and magnetic losses, and

(iii) Multiple reflections (SEM) between internal interfaces.

The total shielding effectiveness (SET) is described as the sum of these components.

According to Schelkunoff's theory, the total EMI shielding effectiveness (SET) is defined as the sum of three primary attenuation mechanisms that decrease electromagnetic wave transmission: reflection loss (SER), absorption loss (SEA), and multiple reflection loss (SEM) (Tian et al., 2023). As shown in Equation (3), this relationship can be written as:

$$SE_T = SE_R + SE_A + SE_M \tag{3}$$

Reflection loss primarily arises when a wave experiences an impedance discontinuity between free space and the surface of the shielding material. Based on plane-wave propagation principles, the SER is governed by the material's electrical conductivity (σ), magnetic permeability (μ), and the frequency (f) of the incoming electromagnetic wave, as expressed in Equation (4).

$$SE_R = 20\log\left(\frac{Z_i}{4Z_s}\right) = 39.5 + 10\log\left(\frac{\sigma^2}{\pi f \mu}\right) \tag{4}$$

Where Zi and Zs represent the impedances of free space and the shielding material, respectively. Here, σ, μ, and f denote the electrical conductivity, magnetic permeability, and frequency of the electromagnetic wave (Chen et al., 2024).

Absorption loss occurs when electromagnetic energy is converted into heat through interactions with mobile charge carriers, dipoles, and magnetic domains. It can be expressed as Equation (5):

$$SE_A = 20\frac{t}{\delta}\log e = 8.68\frac{t}{\delta} \tag{5}$$

Where t is the material thickness and δ is the skin depth, which is defined by (6):

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \tag{6}$$

Thus, absorption loss is directly affected by the material's thickness (t), conductivity (σ), magnetic permeability (μ), and frequency (f) (Tian et al., 2023).

Multiple reflection loss occurs when electromagnetic waves are repeatedly scattered within a material at multiple internal interfaces.

$$SE_M = 20\, log\left(1 - e^{-2t/\delta}\right) \quad (7)$$

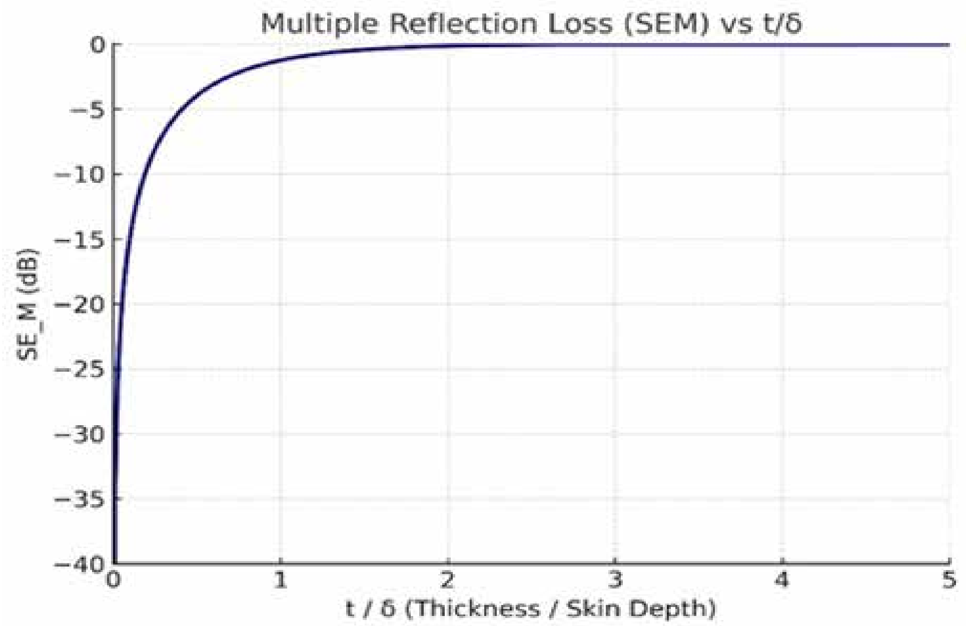
Alternatively, it can be expressed in terms of SEA as:

$$SE_M = 20\, log\left(1 - 10^{-SE_A/10}\right) \quad (8)$$

For thin materials (t < δ), internal reflections extend the propagation path, increasing total EMI SE. In contrast, for thick materials (t > δ), most of the incident energy is absorbed, and multiple reflections become insignificant. This trend is shown in Figure 4.

Figure 4

Variation of Multiple Reflection Loss (SEM) with t/δ Ratio



Therefore, most studies in the literature tend to overlook the SEM component when dealing with relatively thick shielding materials, and they usually evaluate the total EMI SE solely based on the contributions of SER and SEA (Manjunath & Virupaxi, 2025; Tian et al., 2023).

1.5.Specific EMI Shielding (SSE)

Assessing the EMI shielding capability of a material requires consideration of more than its overall shielding effectiveness (SE); the physical attributes of the material—

particularly its density (ρ) and thickness (t)—also play an essential role. For this reason, the parameter known as specific shielding effectiveness (SSE) is used to represent the shielding efficiency normalized by either mass or thickness. This metric is widely regarded as a key engineering indicator for evaluating lightweight yet highly effective materials. SSE not only reflects the inherent shielding performance of a material but also underscores beneficial features such as reduced weight and minimal structural thickness (X. Y. Wang et al., 2022).

In porous or foam-structured materials, the bulk density directly impacts shielding performance. For these systems, SSE is defined as the ratio of the EMI SE to the material density, as given in Equation (9). $(dB \cdot cm^3 \cdot g^{-1})$.

$$SSE_{(foam)} = \frac{EMISE}{\rho} \tag{9}$$

To account for thickness variations in porous structures, the surface-specific shielding effectiveness parameter is used. In this case, SSE is expressed as the ratio of EMI SE to the product of density and thickness as shown in Equation (10). $(dB \cdot cm^2 \cdot g^{-1})$.

$$\frac{SSE}{t}_{(foam)} = \frac{EMISE}{\rho t} \tag{10}$$

For film-type shielding materials, density differences are usually insignificant, and the key parameter becomes the thickness (t), which indicates the EMI protection ability per unit thickness of the film. According to Equation (11), SSE is defined as $(dB \cdot mm^{-1})$:

$$SSE_{(film)} = \frac{EMISE}{t} \tag{11}$$

This expression enables fair comparison among films of varying thicknesses. Although the absorption contribution increases with thickness, SSE(film) generally saturates beyond a specific threshold thickness. Therefore, optimal design emphasizes developing configurations that achieve maximum SE at the least thickness possible.

Since weight reduction is a key design criterion in aerospace applications, the SSE(film) parameter is an excellent indicator for assessing the electromagnetic performance of CFRP layers. For example, CNT/epoxy and MXene-reinforced CFRP laminates have shown SE values of 30–50 dB and SSE(film) levels of 40–60 dB•mm^{-1} with film layers only a few hundred micrometers thick (Zhao et al., 2024; Wang et al., 2023).

Therefore, SSE(film) is considered a crucial engineering metric that enables the simultaneous optimization of high EMI shielding effectiveness and lightweight design in aerospace structural composites.

1.6.EMI Shielding Measurements

The network analyzer is one of the primary instruments used to evaluate electromagnetic interference shielding effectiveness (EMI SE). These analyzers are generally classified into two types: Scalar Network Analyzers (SNAs) and Vector Network Analyzers (VNAs). Whereas an SNA provides information solely on the amplitude of a signal, a VNA simultaneously measures both amplitude and phase. This capability enables the detailed examination of a material's electromagnetic behavior and the determination of properties such as complex permittivity (ε) and magnetic permeability (μ). As a result, the VNA is widely regarded as the instrument of choice for comprehensive EMI shielding assessments.(Cheng et al., 2022).

The VNA functions by transmitting electromagnetic waves over a specified test frequency range through two ports, while simultaneously recording the signals reflected from and transmitted through the sample being tested. These recorded responses are expressed as scattering parameters (S-parameters) and are defined as follows:

S11 is the portion of the incident wave at Port 1 that is reflected to the same port (forward reflection coefficient).

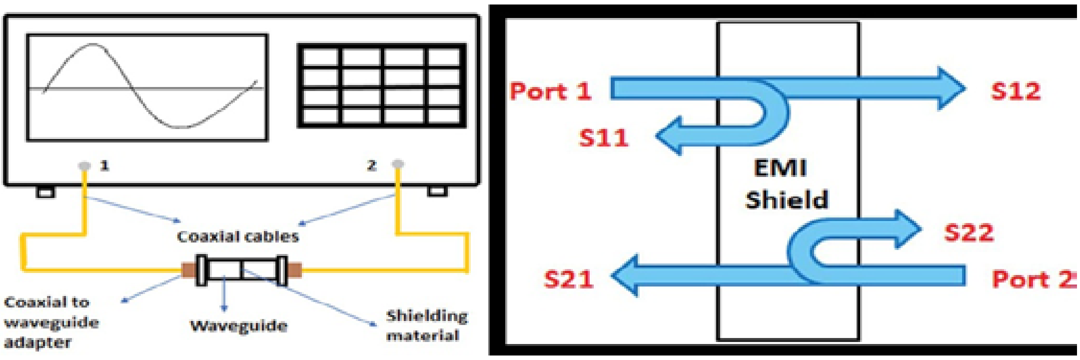
S22 is the part of the incident wave at Port 2 that is reflected to the same port (reverse reflection coefficient).

S21 is the part of the wave that enters from Port 1 and exits through Port 2 (representing the forward transmission coefficient).

S12, the part of the wave entering from Port 2 and exiting through Port 1 (backward transmission coefficient).

Figure 5

Electromagnetic Interference (EMI) Shielding Measurements Systems. a) Vector Network Analyzer, b) Scattering Parameters



The measured S-parameters allow for a quantitative description of how an electromagnetic wave interacts with a shielding material through the transmission (T), reflection (R), and absorption (A) coefficients. These coefficients are determined using the relationships presented in Equations 12–14.

$$R = |S_{11}|^2 = |S_{22}|^2 \tag{12}$$

$$T = |S_{21}|^2 = |S_{12}|^2 \tag{13}$$

$$A = 1 - R - T \tag{14}$$

The Vector Network Analyzer (VNA) allows for determining the key shielding effectiveness components—reflection loss (SER), absorption loss (SEA), and total shielding effectiveness (SET)—measured in decibels (dB) as:

$$SE_R = 10\,log\left(\frac{1}{1-|S_{11}|^2}\right) = 10\,log\left(\frac{1}{1-|S_{22}|^2}\right) = 10\,log\left(\frac{1}{1-R}\right) \tag{15}$$

$$SE_A = 10\,log\left(\frac{1-|S_{11}|^2}{|S_{12}|^2}\right) = 10\,log\left(\frac{1-|S_{22}|^2}{|S_{21}|^2}\right) = 10\,log\left(\frac{1-R}{T}\right) \tag{16}$$

$$SET = 10\,log\left(\frac{1}{|S_{12}|^2}\right) = 10\,log\left(\frac{1}{|S_{21}|^2}\right) = 10\,log\left(\frac{1}{T}\right) \tag{17}$$

Besides the SE components, the VNA results allow for the assessment of additional electromagnetic parameters, including impedance (Z), reflection loss (RL), and effective absorption (Aeff):

$$Z = Z_0\left|\frac{1+S_{11}}{1-S_{11}}\right| \tag{18}$$

$$RL = 20\,log\left(|S_{11}|\right) \tag{19}$$

$$A_{eff} = \frac{1-R-T}{1-R} \times 100\% \tag{20}$$

These relationships provide a comprehensive framework for breaking down the total shielding effectiveness into its physical components and assessing how reflection, absorption, and transmission contribute to the material's overall EMI attenuation performance (Chen et al., 2024; Kumar et al., 2018; Liang et al., 2021).

1.7.Dielectric and Magnetic Behaviour

In EMI shielding, the reflection and absorption capabilities of a material during its interaction with electromagnetic waves are primarily determined by dielectric and magnetic losses. These two mechanisms convert electromagnetic energy within the material into heat and form the basis of the absorption component (SEA). For a shielding material to be effective, both behaviours must be balanced through proper impedance matching. Excessive attenuation can cause surface impedance mismatch, leading to increased reflection, while insufficient attenuation allows wave energy to pass through without adequate dissipation within the material. Therefore, the electrical conductivity (σ), dielectric constant (ε′, ε″), magnetic permeability (μ′, μ″), and thickness (d) of the material should be optimized together. Higher electrical conductivity enhances both reflection and absorption losses, while higher magnetic permeability enhances absorption efficiency and reduces reflection. Notably, incorporating magnetic components with $\mu > 1$ into conductive composites encourages absorption-dominated shielding behaviour, supporting the development of high-performance EMI shielding materials. Consequently, precise design of the complex dielectric constant and complex magnetic permeability parameters is essential for effective electromagnetic wave absorption (Chen et al., 2024).

The dielectric behaviour of a material, determined by its permittivity (ε), describes its capacity to store electrical energy and undergo polarization when exposed to an electric field. When an electromagnetic wave creates an alternating electric field within the material, the bound charges in atoms and molecules try to reorient in response. If this reorientation cannot keep up with the oscillating field, some energy is lost as heat—a phenomenon called dielectric loss. This behaviour is mathematically expressed by the complex permittivity in Equation (21):

$$\varepsilon = \varepsilon^{'} - j\varepsilon^{''} \quad (21)$$

Where ε′ indicates the energy-storage capability, and ε″ signifies the energy dissipation or dielectric loss within the material.

The severity of loss is numerically indicated by the dielectric loss tangent ($\tan \delta_e$):

$$\tan \delta_e = \frac{\varepsilon^{''}}{\varepsilon^{'}} \quad (22)$$

A higher tan δe value indicates stronger absorption of electromagnetic energy and greater conversion into heat. However, an excessively high loss tangent can disrupt impedance matching, leading to increased surface reflections. Therefore, a balanced design of ε′ and ε″ is crucial for optimal EMI shielding performance, as demonstrated in carbon- and polymer-based composites with heterogeneous interfacial structures, enhanced interfacial polarization greatly increases dielectric losses, thereby boosting EMI attenuation efficiency (Tian et al., 2023).

Magnetic behaviour results from the interaction between the magnetic part of an electromagnetic wave and the magnetic dipoles, domain walls, and microscopic current loops inside the material. When the wave enters the medium, the alternating magnetic field causes the magnetic domains to rotate and eddy currents to form. These processes create phase delays, leading to some electromagnetic energy being turned into heat — a phenomenon called magnetic loss.

This behaviour is described by the complex magnetic permeability in Equation (23):

$$\mu = \mu^{'} - j\mu^{''} \tag{23}$$

Where μ′ indicates the material's capacity to store magnetic energy, and μ″ represents the energy lost through magnetic dissipation.

The magnetic loss tangent quantitatively characterizes the magnitude of these losses.

$$\tan\delta_m = \frac{\mu^{''}}{\mu^{'}} \tag{24}$$

A higher tan δ_m value indicates more efficient attenuation of the magnetic component of electromagnetic waves. However, this parameter depends heavily on frequency: at low frequencies, hysteresis and domain wall motion dominate, whereas at higher frequencies, eddy currents, natural resonance, and dimensional resonance become significant. Therefore, achieving a proper balance between high μ′ (magnetic energy storage) and controlled μ″ (magnetic dissipation) is essential for maximizing absorption-dominated EMI shielding performance, especially within the X-band (8–12 GHz) range used in radar, defense, and aerospace applications (Chen et al., 2024).

Together, these dielectric and magnetic mechanisms collectively determine the absorption-dominated shielding behaviour of composite materials. Finding the right balance between electrical polarization and magnetic relaxation enables effective attenuation of incident electromagnetic energy, reducing reflection while increasing energy dissipation within the material. This combined interaction between permittivity and permeability is therefore essential for designing next-generation, lightweight, and broadband EMI shielding composites for aerospace applications.

2.EMI Shielding Effectiveness of Carbon Fiber Reinforced Polymer Composites in Aerospace Structural

Carbon fiber–reinforced polymers (CFRPs) have become essential materials in advanced engineering applications owing to their exceptional specific strength, low density, flexibility, and strong corrosion resistance. Beyond their structural merits, CFRPs are increasingly adopted as efficient EMI shielding components in aerospace systems. Integrating nanostructured fillers with high electrical conductivity or magnetic permeability—such as metallic particles, carbon nanotubes, graphene, or MXenes—can markedly improve the electromagnetic interference shielding performance of these composite materials. (Kim et al., 2023). As a result, CFRPs have become an essential material platform for next-generation aerospace systems that demand lightweight, high-performance, and electromagnetically compatible structures.

In aircraft, unidirectional CFRP laminates are commonly used in primary load-bearing elements such as wing spars and fuselage panels, where high tensile strength and low weight are essential (J. Zhang et al., 2023b). Woven and fabric-based CFRPs are preferred for secondary components such as fairings, flaps, and interior panels, offering balanced properties in multiple directions. In space applications, CFRPs are used in satellite bus structures, antenna reflectors, and payload support frames where dimensional stability and resistance to thermal cycling are critical (Ambhore, 2024). The multifunctionality of these composites, combining mechanical performance with EMI shielding, thermal management, and sensing capabilities, makes them essential materials for modern aerospace systems.

CFRPs used in aerospace structures are categorized not only by their fiber and matrix components but also by their interactions with electromagnetic waves, their shielding effectiveness, and their energy attenuation. This classification provides a crucial perspective and reference framework for understanding the application areas, performance traits, and design approaches of CFRPs in aerospace systems, especially concerning their EMI-related behaviours.

2.1.Classification According to Shielding Mechanism

The EMI shielding performance of CFRPs is primarily dictated by the dominant mechanisms that govern the interaction between the incoming electromagnetic waves and the composite material, specifically reflection, absorption, and successive internal reflections.

Reflection-dominated CFRPs exhibit high surface conductivity, leading to most incident electromagnetic energy reflecting at the air–material interface due to impedance mismatch (Jang et al., 2022; Tserpes, 2025). Conversely, absorption-dominated systems depend on dielectric and magnetic losses within the composite, converting electromagnetic energy into heat through interfacial polarization and eddy-current effects (Romero-Arismendi et al., 2024). Balanced or impedance-matched CFRPs incorporate both conductive and magnetic components, such as CNT–MXene or GR–Fe_3O_4 hybrids, to enable both reflection and absorption with minimal secondary reflections (Duan, Shi, Wang, Zhang, Zhang, et al., 2023; H. Hu et al., 2025)

In multilayered or porous structures, multiple reflection mechanisms become dominant, in which the wave undergoes successive internal scattering and attenuation at stacked conductive–dielectric interfaces (Duan, Shi, Wang, Zhang, Zhang, et al., 2023; H. Hu et al., 2025)

Table 1

Classification of CFRPs Based on EMI Shielding Mechanisms

Category	Description	Dominant Mechanism	Representative CFRP System	Specific Aerospace Application
Reflection-Dominated CFRP	High surface conductivity; most incident EM waves are reflected at the interface due to impedance mismatch.	SER > SEA	Ni- or Cu-coated CFRPs; dense CNT/graphene laminates.	Fuselage skins, radar housings, and aircraft electronic bays — where reflected EM waves must be redirected away from sensitive circuits.
Absorption-Dominated CFRP	Enhanced dielectric/ magnetic losses; EM energy converted into heat inside the composite.	SEA > SER	MXene-, Fe_3O_4-, or ferrite-modified CFRPs.	Engine nacelles, UAV signal housings, and antenna covers, where EM damping and heat dissipation are essential.
Balanced Shielding CFRP	Impedance-matched composites combining conductive and magnetic phases for dual-mode shielding.	SER ≈ SEA	CNT–MXene or CNT–graphene hybrid CFRPs.	Wing leading edges, avionics enclosures, and internal structural panels require both mechanical strength and EMI balance.

Multi-Reflection CFRP	Layered or porous structures promote internal scattering and multi-path attenuation.	High SET via SEM	CNT/BN/CNT or MXene/ GR multilayer sandwiches.	Satellite payload bays, composite radomes, and instrument compartments demanding broadband shielding with low areal density.

2.2.Classification According to EMI Performance Level

The overall shielding performance of CFRPs is measured by their total shielding effectiveness (SET), which sums up the contributions from reflection (SER), absorption (SEA), and multiple reflection (SEM) mechanisms (Kim et al., 2022; Zhang & Wang, 2023). Based on their SET values and functional needs, CFRPs can be classified into different performance levels, from purely structural materials to advanced multifunctional shielding composites used in aerospace applications (Hu et al., 2025; Dong et al., 2025).

Table 2

Classification of EMI Performance Level

Category	Typical SET (dB)	Performance Level	Representative CFRP System	Specific Aerospace Application
Low-Level EMI CFRP	< 20 dB	Primarily structural; minimal EMI protection	Neat CFRP (epoxy + carbon fiber)	Wing spars, fuselage panels, and landing gear doors focus on mechanical strength and weight reduction.
Moderate-Level EMI CFRP	20–40 dB	Partial EMI shielding; enhanced electrical conductivity	CNT or graphene-filled epoxy CFRP	Aircraft interior panels, UAV fuselage sections, and radome interiors require moderate EMI suppression.

High-Level EMI CFRP	40–60 dB	Aerospace-grade composites; balanced reflection and absorption	MXene/CNT hybrid CFRPs or metal-coated fabrics	Avionics housings, engine nacelles, and electromagnetic covers protecting sensitive electronics.
Advanced EMI CFRP	> 60 dB	Superior broadband shielding; multifunctional performance	Ni-coated MXene–graphene sandwich CFRPs	Satellite payload bays, UAV antennas, radar systems, and space communication structures, where broadband attenuation and lightweight design are critical.

2.3.Classification According to Functional Composition

The EMI shielding performance of CFRPs can be tailored by introducing various functional constituents that modify their electrical, magnetic, and interfacial characteristics. Neat CFRPs, consisting only of carbon fibers and polymer matrices, provide limited shielding and serve mainly as structural materials (Vartak et al., 2022). To improve conductivity, metal-coated CFRPs are developed that incorporate metallic or magnetic layers—such as Ni–Fe or Fe_3O_4—that enhance both reflection and absorption (Shukla, 2019). Conductive polymers like PANI, PPy, and PEDOT-PSS are also used, providing lightweight, flexible pathways for charge transfer (Zheng et al., 2024). Carbon-based CFRPs containing CNTs or graphene form continuous conductive networks that enhance both reflection and internal energy dissipation (Thomassin et al., 2013; Zhong et al., 2021). MXene-based CFRPs, with their 2D metallic conductivity and adaptable surface chemistry, show excellent impedance matching and broadband electromagnetic shielding performance (Yuan et al., 2025). Lastly, hybrid CFRPs that combine conductive and magnetic phases, such as CNT–MXene or GR–Fe_3O_4, create synergistic reflection–absorption behaviour ideal for aerospace EMI applications (Irfan et al., 2023a; R et al., 2024)

2.3.1.Neat CFRPs

Neat CFRPs describe carbon fiber–reinforced polymer composites that do not incorporate additional conductive modifiers such as carbon nanotubes, MXenes, or metallic nanoparticles. Because these systems are composed solely of carbon fibers within a polymer matrix, their electrical conductivity and resulting electromagnetic interference (EMI) shielding performance remain inherently modest. For this reason, neat CFRPs are primarily valued for their mechanical advantages, including high specific strength, notable stiffness, strong fatigue resistance, and overall lightweight characteristics (J. Zhang et al., 2023a).

In aerospace and spacecraft structures, neat CFRPs are typically used in primary and secondary load-bearing parts where EMI shielding is not essential. Common examples include wing spars, fuselage skins, rib and frame components, internal structural panels, UAV fuselage beams, and satellite support trusses (J. Zhang et al., 2023a). Using them in these areas ensures optimal structural efficiency, weight savings, and mechanical reliability while keeping design simple and cost-effective compared to multifunctional or filler-modified CFRPs.

Table 3

Applications of neat CFRP in aerospace structures

Application Area	Function in Structure	Typical CFRP Configuration	Remarks
Wing spars and ribs	Primary load-bearing members transfer aerodynamic and structural loads.	Unidirectional carbon fiber/ epoxy laminates.	High stiffness and strength with low weight; limited EMI performance.
Fuselage skins and panels	Outer structural shells provide rigidity and shape retention.	Woven carbon fiber/epoxy composites.	Lightweight and corrosion-resistant; EMI shielding is not critical in these regions.
Internal structural panels	Secondary support structures for interior and control compartments.	Quasi-isotropic CFRP laminates.	Provide dimensional stability and fatigue resistance under cyclic stress.
UAV fuselage beams and frames	Lightweight structural skeleton of uncrewed aerial vehicles.	Carbon fabric-reinforced epoxy composites.	Preferred for weight reduction and mechanical integrity; low electrical conductivity.
Satellite trusses and support frames	Load-bearing and alignment components in satellite and space payload structures.	High-modulus unidirectional CFRP laminates.	Provide stiffness, thermal stability, and dimensional accuracy in vacuum environments.

2.3.2.Metal-coated CFRPs

Metal-coated CFRPs are composite materials in which the carbon fiber surface or outer layer is coated with metallic elements to improve electrical and magnetic properties. Conductive metals such as copper (Cu), nickel (Ni), silver (Ag), and aluminium (Al) are typically deposited onto the CFRP surface via electroplating, sputtering, or electroless coating to create continuous electron pathways and significantly enhance surface conductivity. Conversely, magnetic metals and alloys like cobalt (Co), iron (Fe), and nickel–iron (Ni–Fe) enhance magnetic permeability and induce eddy-current losses, thereby achieving absorption-based electromagnetic shielding. The integration of these conductive and magnetic metals enables the CFRP substrate to display dual electromagnetic responses, reflection and absorption, while preserving structural strength and lightweight qualities crucial for aerospace applications (Ouyang et al., 2025; Xie et al., 2026).

In aerospace and spacecraft structures, metal-coated CFRPs are frequently used in areas where both mechanical performance and electromagnetic compatibility are crucial. Typical applications include avionics housings, engine nacelles, radar fairings, satellite antenna supports, and electronic bay enclosures. Here, metallic coatings protect sensitive systems from external EMI and help dissipate accumulated charges. Nickel- or copper-coated CFRP laminates are especially preferred for fuselage panels and UAV body structures because they improve conductivity without adding significant weight. In high-frequency or demanding environments, Ni-Fe-coated or hybrid metallic films offer stable shielding across wide temperature ranges and radiation conditions. These multifunctional metal-coated CFRPs thus connect traditional structural composites with active electromagnetic shielding materials in next-generation aerospace systems (Pang et al., 2023; Wu et al., 2025; Yuanzhi et al., 2025)

Zhu and co-workers (2021) developed Ni-coated carbon fiber fabric/epoxy composites by applying electroless nickel plating followed by polydopamine (PDA) interfacial modification. This interface-engineered structure reached an EMI shielding effectiveness (SE) of about 31 dB, representing roughly a 77% improvement over uncoated CFRP, while also significantly improving interlaminar shear and tensile strength. Such Ni-modified CFRP systems are promising for aircraft fuselage panels, avionics housings, and access covers that require both load-bearing capacity and EMI shielding (Zhu et al., 2021).

Zhu and colleagues fabricated Ag/T-ZnO interlayered CFRP laminates by inserting silver-coated tetra-needle ZnO sheets between CF/epoxy layers through vacuum infusion. The structure achieved an EMI SE of approximately 40.99 dB (8.2–12.4 GHz), which is about 26.5 dB higher than the unmodified CFRP reference. Such Ag-interlayered CFRP skins are promising for radome-adjacent panels, avionics bay covers, and instrument fairings that need lightweight shielding (Zhu et al., 2025).

Liu and colleagues developed Ni–Fe nanoparticle-coated carbon fibers to create conductive fiber networks for EMI shielding composites. Ni and Fe nanoparticles were chemically deposited onto the carbon fiber surfaces, producing a hybrid magnetic–conductive network that simultaneously strengthened reflection and absorption losses. The engineered composite exhibited an EMI shielding effectiveness of around 52 dB within the X-band, supported by improved impedance matching and enhanced mechanical integrity. CFRP systems modified with such Ni–Fe coatings show strong potential for use in aerospace structural panels, electronic enclosure components, and UAV payload casings, where ultralight materials that integrate magnetic loss mechanisms with electrical conductivity are essential for achieving high-performance EMI shielding (Ouyang et al., 2025).

Table 4

EMI shielding performance and aerospace applications of metal-coated CFRPs

Metal Type	Functional Role	Typical Coating Method	Aerospace Application	Typical EMI SE (dB)	Specific SE (dB•mm^{-1})
Copper (Cu)	Provides high surface conductivity for reflection-dominated EMI shielding.	Electroplating, electroless deposition.	Avionics housings, fuselage panels, and UAV body shells for improved charge dissipation.	45–55 dB (8–18 GHz)	100–180 dB•mm^{-1}
Nickel (Ni)	Enhances both electrical conductivity and moderate magnetic loss, providing a hybrid EMI response.	Electroless plating, sputtering, or thermal spraying.	Engine nacelles, radar fairings, and satellite panels require balanced shielding and strength.	50–65 dB (0.5–18 GHz)	90–160 dB•mm^{-1}

Silver (Ag)	Exhibits excellent electrical conductivity with minimal thickness; enables high-frequency shielding.	Physical vapor deposition (PVD), sputtering.	Communication antennas, satellite enclosures, and aerospace sensors.	60–70 dB (2–26 GHz)	160–300 dB•mm^{-1}
Aluminium (Al)	A lightweight, conductive coating improves surface reflectivity while maintaining low density.	Thermal spraying or vapor deposition.	Aircraft fuselage skins and interior structural panels emphasize weight efficiency.	40–55 dB (8–12 GHz)	80–140 dB•mm^{-1}
Nickel–Iron (Ni–Fe) alloy	Provides magnetic permeability and eddy current losses for absorption-dominated shielding.	Electrochemical co-deposition or sputtering.	High-frequency shielding layers in radar systems and spacecraft components.	65–80 dB (1–18 GHz)	140–250 dB•mm^{-1}

2.3.3. Conductive Polymers

Conductive polymers (CPs) are a class of π-conjugated organic materials capable of transporting charge through delocalized π-electrons along their molecular backbone. Typical examples, such as polyaniline (PANI), polypyrrole (PPy), polythiophene (PTh), and PEDOT, exhibit electrical conductivities ranging from 10^{-4} to 10^{3} S/cm, depending on the degree of doping and structural order (Zheng et al., 2024). Their conjugated structure and mobile charge carriers enable high dielectric polarization and efficient conversion of electromagnetic energy into heat, which is the primary mechanism of absorption-dominated EMI shielding. These polymers can be processed into thin, uniform, corrosion-resistant coatings, enabling flexible and conformal EMI barriers. Recent studies have shown that PANI- and PPy-based composites can achieve 40–70 dB SE in the X-band range due to enhanced interfacial polarization and impedance matching (Turczyn et al., 2020)

In aerospace structures, conductive polymers are increasingly used as interlayers, coatings, or hybrid matrices within carbon-fiber composites to preserve electromagnetic compatibility without adding excessive weight. Their low density, chemical stability, and adjustable conductivity make them suitable for radomes, fuselage skins, and antenna housings, where metallic shields might cause galvanic corrosion or increase weight. Therefore, CP-based systems are seen as crucial components of next-generation lightweight, multifunctional aerospace composites that combine structural performance with EMI protection (Alemour et al., 2019; Das & Prusty, 2012; Yadav et al., 2020).

Table 5

EMI shielding performance and aerospace applications of Conductive Polymers

Conductive Polymer Type	Functional Role	Typical Integration Method	Aerospace Application	Typical EMI SE (dB)
Polyaniline (PANI)	Forms conductive networks and enhances interfacial polarization; absorption-dominant	In-situ polymerization on CF fabric/ epoxy matrix	Aircraft fuselage panels, avionics enclosures	≈ 54.8 dB (Kong et al., 2022)
PANI–MoS_2 hybrid	Provides multiple interfacial polarizations and dielectric loss	Surface functionalization and chemical oxidative coating	Radomes, dielectric transparent covers	≈ 41 dB (Zhou et al., 2025)
Polypyrrole (PPy)	Improves conductivity and magnetic loss balance; stable coating	In-situ chemical polymerization on the CF surface	Avionics housings, inner structural panels	≈ 74 dB (Li et al., 2024)
PANI/MXene hybrid composite	Enhanced absorption and impedance matching through conductive–dielectric coupling	Vacuum-assisted infiltration into CFRP layers	Multifunctional fuselage structures, sensor-integrated composites	≈ 62 dB (Z. Wang et al., 2021)

2.3.4. Carbon-based CFRPs

Carbon-based CFRP composites incorporate conductive nanocarbon materials mainly carbon nanotubes (CNTs) and graphene or graphene nanoplatelets (GNPs), into traditional CFRP matrices to produce lightweight, multifunctional materials with excellent EMI shielding and structural capabilities.

Carbon-based CFRPs are typically categorized into two main groups. The first includes CNT-based CFRPs, where CNTs are either grown directly on carbon fibers or added as thin interlayers (buckypaper) to enhance electrical pathways between fibers. The second comprises graphene-based CFRPs that use graphene or reduced graphene oxide (rGO) sheets as coatings or interleaved layers to enhance polarization and absorption. Both types are designed for aerospace parts such as fuselage panels, radomes, antenna housings, and avionics enclosures, where EMI shielding values of 30-70 dB are usually required (Kim et al., 2023; Suresha et al., 2025; H. Zhang et al., 2023)

In aerospace structures, carbon-based CFRPs are strategically used in fuselage skins, radomes, antenna housings, and avionics enclosures where both high EMI attenuation and weight reduction are required. Recent studies also show that these materials can effectively shield EMI while maintaining lightweight aircraft structures. (Kim et al., 2023) developed CFRP laminates reinforced with in-situ-grown CNTs, achieving an EMI shielding effectiveness (SE) of over 70 dB across the 0.3–1.5 GHz frequency range. These composites enhance charge transfer between the fibers and the matrix, making them suitable for avionics housings and internal EMI barriers. (Suresha et al., 2025) created graphene nanoplatelet (GNP) reinforced CFRP laminates with an SE of 32.4 dB in the X-band (8–12 GHz), recommending them for radome skins and electronic covers due to their corrosion resistance and light weight. Patadia et al. (2024) designed high-strength CFRP panels that achieved over 80 dB EMI SE across the X-band, demonstrating that carbon-based composites can replace metallic shields in fuselage and skin panels. Finally, (Yang et al., 2024) reviewed graphene-coated CFRP structures and highlighted their lightweight nature, corrosion resistance, and absorption-based shielding, making them ideal for radomes and antenna housings in modern aircraft.

These studies show that carbon-based CFRPs are becoming key materials for multifunctional aerospace structures, providing both mechanical performance and electromagnetic compatibility in advanced aircraft and spacecraft systems.

Table 6

EMI shielding performance and aerospace applications of Carbon-based CFRPs

CFRP Type	Representative Nanocarbon Additive	Structural Description / Integration Strategy	Aerospace Application	Typical EMI SE (dB)	Specific SE (dB•mm^{-1})

CNT-Modified CFRP	Multi-walled or single-walled carbon nanotubes (MWCNTs/ SWCNTs)	CNTs grafted on carbon fibers or embedded as buckypaper interlayers to create 3D conductive networks and improve through-thickness conductivity	Fuselage panels, avionics enclosures, internal EMI partitions	50–60 (Kim et al., 2023)	35–45
Graphene-Modified CFRP	Graphene nanoplatelets (GNP), reduced graphene oxide (rGO)	Graphene coatings or interleaves enhance dielectric loss and interface polarization; provide corrosion-resistant EMI shielding	Radomes, antenna housings, composite fairings	60–70 (Suresha et al., 2025)	40–55
CNT/ MXene-Reinforced CFRP	CNTs + $Ti_3C_2T_x$ MXene nanosheets	Hybrid conductive–dielectric coupling; enhanced absorption and mechanical stability	Structural EMI shielding panels, smart fuselage composites	65–75 (J. Dong et al., 2025)	50–60

2.3.5.MXene-based CFRPs

MXene-based CFRP composites are a new type of lightweight, multifunctional materials that incorporate two-dimensional $Ti_3C_2T_x$ MXene nanosheets into carbon fiber/epoxy systems. This integration can be achieved through surface coating of carbon fabrics, insertion of MXene interleaves, or direct functionalization of the fiber surface. The resulting structures demonstrate high electrical conductivity, broad-band absorption, and excellent interfacial compatibility, making them promising options for next-generation EMI shielding in aerospace applications (Liu et al., 2023; Q. Zhang et al., 2023)

Several recent studies have examined the direct integration of MXenes into CFRP systems, reporting significant improvements in electromagnetic shielding performance. Yilmaz et al. (2025) produced MXene-sprayed carbon fabric/epoxy CFRP laminates using vacuum infusion. They achieved an overall EMI SE of approximately 32 dB in the X-band, along with improved interlaminar shear and flexural strength—demonstrating a scalable fabrication method for multifunctional CFRP structures. According to Zhang et al. (2024), coated CF/PEEK thermoplastic CFRP tapes with $Ti_3C_2T_x$ MXene to enhance interfacial bonding, reporting a specific EMI SE of about 80.8 dB•mm^{-1} and framing their work within a clear aerospace context (Zhang et al., 2024). Similarly, Irfan et al. (2023b) fabricated MXene-coated aerospace-grade fiber composites with dual EMI shielding and sensing capabilities, noting superior attenuation compared to rGO-coated counterparts. Finally, Duan et al. (2023) developed a $Ti_3C_2T_x$-MXene/graphene oxide interleaved carbon-fabric composite that achieved approximately 38 dB SE in the X-band, providing a design model easily adaptable to CFRP laminates for aerospace applications.

Table 7

EMI shielding performance and aerospace applications of MXene-based CFRPs

Composite System	EMI SE (dB)	Main Features and Findings	Application / Remarks
$Ti_3C_2T_x$ MXene / GO/carbon fabric multilayer	38 dB	Flexible multilayer architecture; absorption-dominant shielding; stable under bending.	Scalable thin shielding films for aerospace panels. (Duan et al., 2023)
Recycled carbon fiber (MXene-coated) sandwich paper	45.7 dB	Lightweight, recyclable, and highly conductive; high specific SE per thickness.	Potential EMI shields for aircraft interiors and UAV bodies. (Liu et al., 2022)
MXene-sprayed carbon fabric/epoxy laminate	32.8 dB	Improved fiber–matrix adhesion and conductivity; strong laminate.	Structural EMI shielding for aerospace components. (Yilmaz et al., 2025)
$Ti_3C_2T_x$ MXene-coated CF/PEEK thermoplastic tapes	80.8 dB•mm^{-1} (specific SE)	Strengthened interfacial bonding; very high specific EMI SE; thermoplastic processing suitable for aircraft.	Explicitly aerospace-oriented CFRP design with dual mechanical-EMI functionality. (Zhang et al., 2024)

Although MXene-CFRPs have proven to be excellent EMI shielding materials, their direct application in real aerospace structures remains limited. Most work still occurs at the laboratory or prototype level. However, future opportunities are clear: MXene-based CFRPs are ideal for radomes, antenna housings, avionics enclosures, fuselage skins, and satellite fairing panels, where low weight and effective EMI absorption are essential. As surface engineering and oxidation-stability challenges are addressed, these multifunctional composites are expected to play a significant role in next-generation lightweight aerospace systems (Iqbal et al., 2020; Lang et al., 2024).

2.3.6.Hybrid CFRPs

Hybrid CFRP composites are advanced multifunctional systems in which two or more types of conductive or magnetic nanomaterials are embedded in the CFRP matrix or layered structure to create synergistic effects. In these hybrids, the traditional carbon fiber/epoxy or CF/PEEK framework is combined with various functional nanofillers, such as CNT + graphene, MXene + metal nanoparticles (Ag, Ni, Fe_3O_4), or conductive polymer + carbon-based nanofillers. These multiscale designs leverage the complementary mechanisms of conduction and polarization loss to enhance impedance matching and enable broadband, absorption-dominant EMI shielding. The resulting hybrid CFRPs offer mechanical strength, thermal stability, and electrical conductivity, which are highly valued for aerospace fuselage panels, antenna radomes, and avionics housings where lightweight multifunctionality is essential (Anggereni & Tahir, 2025; Gao et al., 2023).

Recent Scopus-indexed studies confirm the excellent EMI shielding capabilities of hybrid CFRPs. Zhang et al. (2024b) fabricated a graphene/MXene-coated CF/epoxy laminate, achieving a total EMI SE of around 68 dB in the X-band through combined absorption and reflection; the authors proposed its use for aircraft skin structures. Liu et al. (2023) developed a Ni-CNT hybrid network integrated into CFRP laminates, reaching approximately 72 dB shielding while maintaining mechanical integrity, demonstrating its suitability for aerospace electronic housings. (Yilmaz et al., 2025) reported a MXene/graphene oxide-modified carbon-fabric/epoxy composite with an EMI SE over 60 dB and enhanced conductivity, recommending it for fuselage and radome shells. Similarly, Wang et al. (2022) achieved an impressive 80 dB EMI SE in CNT/Fe_3O_4-decorated CFRP, highlighting magnetic–conductive hybrid coupling as an effective means to enhance attenuation.

Table 8

EMI shielding performance and aerospace applications of Hybrid CFRPs

Hybrid System	Matrix / Substrate	EMI SE (dB)	Dominant Mechanism	Suggested Aerospace Application

Graphene / MXene hybrid coating	CF/Epoxy laminate	68 dB (X-band)	Synergistic absorption + reflection	Suitable for aircraft skin panels and outer fuselage shells, providing high absorption and structural compatibility.(Hu et al., 2024)
Ni-CNT hybrid network	CF/Epoxy composite	72 dB (X-band)	Conductive + magnetic loss coupling	Effective for avionics housings and electronic bays, offering strong EMI attenuation with minimal mass increase. (Liu et al., 2023)
MXene / Graphene-oxide modified carbon fabric	CF/Epoxy laminate	> 60 dB (X-band)	Interfacial polarization + absorption	Applicable to radome and fuselage panels, ensuring broadband EMI absorption and improved interfacial conductivity. (Patadia et al., 2024)
CNT / Fe_3O_4 decorated carbon fiber fabric	CF/Epoxy laminate	80 dB (X-band)	Magnetic–conductive hybrid coupling	Designed for antenna fairings and electronic enclosures, achieving ultrahigh EMI SE through magnetic–conductive synergy. (Wang et al., 2022)

Overall, these results demonstrate that hybrid nanostructures effectively achieve EMI shielding above 60 dB while maintaining the lightweight and structural benefits of traditional CFRPs. This makes them important materials for future aerospace applications.

Conclusion and Future Perspectives

Carbon fiber reinforced polymer (CFRP) composites remain essential materials for aerospace structures, valued for their high specific strength, stiffness, and lightweight nature. As electronic density in aircraft, satellites, and UAV platforms continues to increase, the need for structural components that also provide reliable electromagnetic interference (EMI) shielding has become critical. While neat CFRPs offer moderate shielding from their intrinsic conductivity, they are insufficient for protecting sensitive systems such as radar modules, navigation electronics, and high-frequency communication units.

Recent research demonstrates that modifying CFRPs with conductive or magnetic nanomaterials—such as MXenes, CNTs, graphene, or metal coatings—can achieve shielding effectiveness levels of 50–80 dB in the X-band without sacrificing mechanical performance. These enhanced composites show strong potential for integration into fuselage skin panels, radomes, antenna fairings, avionics bay covers, payload housings on UAVs, and satellite instrument enclosures, where lightweight EMI protection and structural reliability must be combined.

Despite these advancements, challenges remain regarding scalable manufacturing, environmental durability, and the lack of standardized testing protocols tailored to aerospace conditions. Future research should emphasize large-scale process optimization, hybrid filler architectures, and comprehensive evaluation under aerospace-specific thermal, mechanical, and vibration loads. With such developments, hybrid-modified CFRPs are positioned to evolve into true multifunctional materials capable of simultaneously carrying structural loads and ensuring robust EMI protection across next-generation aerospace platforms.

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Drone Swarm Technology: Theory, Architecture, And Applications

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Introduction

Swarm drone technology represents a next-generation paradigm for autonomous systems in which multiple UAVs exchange information and respond to environmental inputs to achieve coordinated motion toward specific goals. Rooted in the harmonious locomotion observed in flocks of birds, schools of fish, and insect swarms, the approach addresses engineering needs for coordination, resilience, and scalability. Designed to exceed the physical and operational limits of single-vehicle platforms, swarm structures excel in scenarios requiring broad area coverage or complex, interdependent tasks through capabilities such as collective decision-making, distributed task execution, and synchronized maneuvers. Representative applications include search-and-rescue, agriculture, industrial inspection, environmental monitoring, logistics, and entertainment displays.

Definitions and Scope

A “swarm drone” system comprises numerous autonomous aerial vehicles that communicate directly or indirectly to exhibit collective behavior. Each vehicle is equipped with its own sensors, onboard processing, and decision-making algorithms; the system-level behavior emerges from the aggregation of local interactions.

Analytically, these systems can be viewed at two complementary levels:

- Local interaction level: Each drone exchanges information primarily with its neighbors, without reliance on a central controller.
- Global task level: The swarm collectively pursues a mission objective—such as area coverage, target tracking, or formation maintenance.

This study focuses on theoretical principles, architectural design, sensing and control methodologies, communication network structures, and representative applications of swarm drone systems. Our aim is to synthesize existing approaches into a coherent framework useful to both academic researchers and engineering practitioners.

Why Swarm? Motivation and Added Value

While single UAVs are effective in many contexts, they remain constrained by range, energy capacity, payload limits, and sensitivity to environmental uncertainty. A swarm-based framework mitigates these constraints through distributed task allocation: individual units contribute to global success by acting on information shared within the group.

Grounded in the principles of swarm intelligence, the approach leverages simple local decision rules to produce complex, emergent system-level behaviors—often without centralized control. The structure also enhances fault tolerance and mission continuity: if a single unit fails, remaining agents can assume its responsibilities, preserving operational integrity in dynamic environments.

Research Aim, Problem, Questions, and Hypotheses

Aim.This chapter unifies theory, architecture, and implementation practices for UAV swarms, offering a practical roadmap for both academic studies and engineering deployments.

Problem.Current practice is fragmented across control, networking, perception, and regulation, which raises integration risk and limits reproducibility and scale.

Research Questions

RQ1: Which control/communication patterns most robustly maintain formations under delay, loss, and partial failures?

RQ2: How do VIO/SLAM pipelines compare to GNSS/RTK in GPS-denied multi-UAV coordination?

RQ3: Which task-allocation strategies (auction/MIP/MARL) best balance energy, coverage, and response time at different swarm sizes?

RQ4: Which safety–security co-design practices harden swarms against jamming/spoofing without degrading performance?

Hypotheses

H1: Consensus-based distributed formation control with QoS-aware middleware outperforms centralized schemes under moderate delay/loss.

H2: Collaborative VIO/SLAM with federated filtering achieves mission-grade accuracy for indoor/urban canyons approaching RTK stability.

H3: Hybrid planners that combine auction pre-assignment with MARL online adaptation yield superior coverage-to-energy ratios beyond 20 UAVs.

H4: Layered safety (failsafe/geofence/isolated landing) with authenticated, encrypted links significantly reduces cascade failures in adversarial events.

Overview of Application Scenarios

Swarm drones can be deployed across missions of varying scale, including post-disaster mapping, agricultural spraying, power-line inspection, industrial site surveillance, logistical support, and coordinated light shows. Common to these scenarios are requirements for tight synchronization, sustained communication, and heightened environmental awareness. Success therefore depends not only on individual platform capabilities but also on the overarching system architecture—communication protocols, data-sharing strategies, and control algorithms.

Consequently, the advancement of swarm drone technology hinges on the integrated evolution of hardware, algorithmic intelligence, network design, and real-time decision systems, rather than hardware progress alone.

History and Current State

Swarm-drone research grew out of efforts to translate collective motion in nature into engineering practice. Phenomena long examined in biology—flocking birds, schooling fish, swarming insects—suggested that large groups can coordinate through simple local interactions. From the 1980s onward, these insights were progressively formalized, and today swarm UAVs sit at the intersection of control theory, artificial intelligence, communications, and embedded systems.

Biological Inspiration and Its Engineering Translation

Natural swarms exhibit coherent, adaptive motion that arises from uncomplicated rules followed by individuals. Migratory V-formations, ant trail organization, and the synchronized maneuvers of fish are representative examples.

Reynolds' Boids (1987) provided an influential computational demonstration: by implementing three local policies—maintaining personal space, aligning headings, and staying near the group—agents produce globally coordinated movement without a central supervisor. This idea catalyzed the development of control schemes for autonomous aerial collectives, allowing key properties of biological swarms—self-organization and adaptability—to inform UAV swarm design.

Early Academic Trajectory and Development Milestones

By the late 1990s, multi-agent systems had become a core topic in robotics, with most swarm studies confined to simulation due to hardware and sensing limits.

The early 2000s brought practical enablers: lightweight processors, reliable short-range radios, and compact sensors made coordinated multi-robot experiments feasible in laboratories. Concepts such as micro-robot swarms and aerial multi-agent networks entered routine academic discourse.

After 2010, open-source flight stacks and tooling (e.g., PX4, ArduPilot), along with research platforms and simulators (e.g., Crazyswarm, ROS-based ecosystems, high-fidelity simulation tools), accelerated prototyping. Academic demonstrations began to transition toward fieldable systems.

Industrial Maturation and Contemporary Directions

Swarm drones have moved beyond purely academic artifacts and now appear across defense, commercial, and civic applications.

In defense contexts, autonomy at scale is explored for missions such as surveillance, electronic attack/denial, and coordinated target engagement.

On the civilian side, prominent uses include precision agriculture, disaster assessment, power-line and infrastructure inspection, logistics support, and large-scale light shows. In many of these scenarios, performance hinges on robust formation control and effective task allocation aided by AI on the edge.

Current research clusters around three themes:

1. Reliable localization without GPS: Techniques that maintain accuracy in indoor,obstructed, or low-signal environments.

2. Edge AI and real-time decision pipelines: On-board inference to cut latency and reduce dependence on constant backhaul links.

3. Scaling coordination: Methods that keep hundreds of vehicles stable, safe, and responsive under realistic communication and failure conditions.

Taken together, these advances position swarm UAVs as core components of future autonomous, mission-level tasking infrastructures.

Theoretical Foundations

Understanding and effectively designing swarm drone systems necessitates an integrated evaluation of multi-agent systems theory, network science, control theory, and collective behavior models. These disciplines provide a theoretical framework elucidating dynamics from individual decision-making processes to the stability of collective motion.

This section addresses three primary theoretical structures underpinning swarm dynamics: multi-agent systems theory, graph-based modeling, and consensus dynamics alongside Boids and potential field approaches.

Multi-Agent Systems and Game Theory-Based Interactions

Swarm drones inherently constitute a distributed system formed by numerous agents engaged in continuous information exchange. Despite possessing limited information, each agent makes local decisions based on inputs from its surroundings, resulting in emergent collective behavior at the swarm level.

Multi-agent systems theory facilitates the mathematical modeling of these interactions. The system is typically represented via differential equations or discrete-time dynamic models. Each drone's state variables—such as position, velocity, and orientation—are updated according to information from neighboring units.

Game theory analytically examines this process: treating each drone as a "player," individual strategic decisions determine the system's equilibrium. Cooperative games, in particular, are employed for mathematical solutions to topics like task allocation and energy optimization in swarms.

This perspective demonstrates that swarms can be modeled not merely as mechanical systems but also as networks of rational decision-makers.

Graph Theory, Laplacian, and Consensus Dynamics

The network structure of swarm systems is expressed through graph theory. Each drone is represented as a node, while information flow between two drones constitutes an edge.

This representation enables analysis of properties such as connectivity and stability. The graph's Laplacian matrix reflects the structural characteristics of information flow within the swarm. The eigenvalues of the Laplacian matrix dictate the system's synchronization capability and consensus speed.

Consensus dynamics is a control principle aiming for all individuals in the swarm to converge to a common value in a specific variable (e.g., direction, velocity, position, or task parameter). This dynamic is generally expressed in differential equation form as:

$$\dot{x}_i = -\sum_{j \in \mathcal{N}_i} a_{ij} (x_i - x_j)$$

where x_i denotes the state of the i-th drone; a_{ij} represents the influence of the j-th drone on the i-th; and $\mathcal{N}_i$ indicates the neighborhood set of i.

This structure determines the swarm's collective stability based on the topology of information sharing. Strong connectivity of the graph ensures the swarm converges to a single formation or decision without dispersion.

Boids and Potential Field-Based Models

The most intuitive explanations of swarm behaviors are provided by the Boids model and potential field approaches.

The Boids model is a simplified behavioral system wherein each drone moves according to three fundamental rules:

- Cohesion: Tendency to approach neighbors, preserving swarm integrity.
- Separation: Avoidance of excessive proximity to prevent collisions.
- Alignment: Mimicking neighbors' orientations to ensure fluid swarm motion.

The potential field model, conversely, generates virtual attractive and repulsive fields around each drone. These fields facilitate orientation toward targets while enabling repulsion from obstacles.

Mathematically, this method relies on updating each drone's motion based on the gradient of total potential energy:

$$F_i = -\nabla U_i(x)$$

where $U_i(x)$ is the potential function defined relative to the i-th drone's position. This approach allows the swarm to adapt to dynamic obstacles, maintain formations, and flexibly redirect toward new targets.

Swarm Architectures

In swarm drone systems, the architectural structure determines the communication patterns among individual drones, the distribution of decision-making authority, and the direction of information flow. Depending on the application scenario, this structure can be designed as centralized, decentralized, or hybrid.

Each architectural approach has distinct advantages and limitations; thus, system design must consider task type, environmental conditions, energy capacity, and reliability requirements.

Centralized Architecture

Centralized architecture involves a structure where the overall behavior of the swarm system is managed by a single control unit. In this setup, a "leader" drone or ground station aggregates information from all drones, formulates a global plan, and dispatches task or formation commands to each individual.

The primary advantage of this approach is decision coherence and global optimization potential; the swarm operates under a unified strategy, with control algorithms relatively straightforward to implement.

However, centralized structures face evident challenges in scalability and reliability. Failure of the control unit can compromise the entire system, while communication delays and bandwidth constraints degrade performance as swarm size increases.

Consequently, centralized architecture is typically preferred for small-scale swarms or predefined mission profiles.

Decentralized (V2V) Architecture

Decentralized architecture constitutes a structure wherein each drone makes decisions based on local information while maintaining direct communication with neighbors. This communication occurs via vehicle-to-vehicle (V2V) links.

The core feature of this approach is the system's ability to self-organize independently of a central authority. Each drone updates its behavior solely according to the position, orientation, or task status of nearby units, thereby enhancing flexibility and fault tolerance.

Decentralized structures are particularly suitable for dynamic environments or tasks involving uncertainty. Even if one drone fails, the overall system can continue functioning.

Nevertheless, the primary challenge lies in ensuring stability and synchronization. Communication disruptions or information delays may lead to formation disruptions within the swarm. Thus, consensus-based control algorithms play a critical role in decentralized systems.

Hybrid Approaches

Hybrid architecture integrates the strengths of centralized and decentralized structures. In this model, strategic decisions are made centrally, while lower-level maneuvers or local coordination tasks are executed decentrally.

For instance, a mission plan may be generated by a central controller; however, en route to the target, drones can communicate locally to handle collision avoidance or obstacle evasion autonomously.

Hybrid approaches offer an optimal balance in scalability, resilience, and mission continuity. However, their design requires clearly delineating task boundaries across communication levels to prevent information conflicts or decision inconsistencies.

Recent studies aim to integrate hybrid structures with the cloud-edge computing paradigm, enabling strategic decisions in the cloud while edge processors handle local control tasks.

Homogeneous and Heterogeneous Swarms

Swarm architecture is defined not only by information flow but also by functional diversity among units.

Homogeneous swarms consist of drones with identical hardware and software, facilitating straightforward control algorithm design and symmetric behavior.

In contrast, heterogeneous swarms incorporate drones of varying capabilities to enhance task efficiency. For example, some may carry high-resolution cameras, while others serve as carriers or communication relays.

Heterogeneous structures impart task versatility and adaptability to the swarm but increase control algorithm complexity. Accordingly, task assignment, resource management, and communication standardization are paramount in such swarms.

Communication and Network Layer

The success of swarm drone systems depends not only on individual flight capabilities but also on the continuity of information exchange among units and the reliability of the communication infrastructure.

The communication infrastructure enables the sharing of position, velocity, sensor data, and task parameters across the swarm. This layer functions as the "neural network" in the swarm's collective decision-making processes; thus, the network's structure and resilience directly influence overall system stability.

This section examines communication protocols, network topologies, quality parameters, and resilience strategies used in swarm drones.

Communication Protocols and Data Structures

Communication in swarm drones typically occurs via low-latency, lightweight data packets. Protocols vary based on task type and system scale.

Common protocols include:

- MAVLink (Micro Air Vehicle Link): An open-source, lightweight binary message protocol (XML) for transmitting telemetry, commands, and sensor data between drones and ground stations. Its simplicity makes it widely used in embedded systems.

- ROS 2 DDS (Data Distribution Service): A publish-subscribe model-based infrastructure for data sharing in distributed systems. ROS 2's DDS architecture effectively manages high-volume data traffic within swarms.

Custom UDP/TCP Protocols: In research settings, bespoke designs facilitate low-level control and experimental data exchange.

Through these protocols, each drone periodically broadcasts information such as position, velocity, orientation, battery level, and task status across the network, allowing real-time monitoring of the local environment by all units.

Mesh and Swarm Network Topologies

Communication in swarm drones is typically built on mesh or swarm-aware topologies.

- Mesh network structure provides a communication network where each drone acts as both transmitter and router. This compensates for failures at any node through redundant surrounding links.

- Swarm network structure extends the classic mesh by accounting for drones' motion dynamics. Connections dynamically reshape based on physical proximity, signal quality, and task priority.

These flexible topologies enable swarm self-organization. For instance, a drone venturing beyond range during a mission can maintain indirect connectivity via other swarm members.

Modern swarm systems integrate these with ad-hoc networking principles and, when necessary, 5G/6G-based infrastructures.

Latency, Bandwidth, and Quality of Service (QoS)

In swarm drones, communication latency and bandwidth are two critical parameters directly impacting system performance.

In real-time tasks (e.g., collision avoidance or formation control), millisecond-level delays can cause significant instability. Protocols must thus be configured for deterministic scheduling and priority-based data flows.

QoS (Quality of Service) refers to classifying network traffic by importance. For example, position updates can be processed as high-priority packets, while low-priority sensor data tolerates delays.

Modern infrastructures like ROS 2 DDS optimize swarm network performance through dynamic QoS policy adjustments.

Resilience and Error Management

Swarm systems must maintain resilience against external interference, signal fading, or hardware failures.

To this end, the following strategies are typically implemented at the communication layer:

1. Multi-link approach: Drones maintain multiple channels (e.g., Wi-Fi + LTE) simultaneously for redundancy against disruptions.

2. Automatic routing updates: Upon link failure, the network topology self-reorganizes, sustaining data flow via alternative paths.

3. Interference immunity: Frequency-hopping spread spectrum (FHSS) or narrowband modulation reduces interference effects.

4. Energy-aware communication: As battery levels drop, transmission shifts to lower frequencies, enhancing efficiency.

These mechanisms render the swarm drone network adaptive and self-healing against both internal (failures) and external (interference, signal loss) threats.

Positioning and Sensing

In swarm drone systems, positioning and sensing comprise foundational components enabling units to accurately determine both their individual positions and those relative to each other and the environment.

This infrastructure establishes the swarm's collective situational awareness, directly impacting the performance of higher-level tasks such as formation control, collision avoidance, and target tracking.

Positioning technologies typically rely on satellite-based systems, visual odometry, and sensor fusion. However, as many are susceptible to environmental conditions, multi-sensor integration is preferred in swarm systems.

GNSS, RTK, and GPS-Denied Positioning Methods

The most prevalent positioning infrastructure in swarm drones is GNSS-based (Global Navigation Satellite System). GNSS systems (GPS, GLONASS, Galileo, BeiDou) provide global-scale position data to drones; yet, signals may degrade in enclosed spaces or high-interference environments.

RTK (Real-Time Kinematic) technology addresses this by incorporating correction data from ground stations to reduce GNSS errors to centimeter-level accuracy. It is favored for precision-demanding formation flights.

For GPS-denied environments (e.g., tunnels, indoors, or dense foliage), alternative methods include:

- Integration of accelerometer and gyroscope data (dead reckoning),
- Magnetic field mapping (magnetic fingerprinting),
- Local RF or UWB (Ultra-Wideband)-based positioning systems,
- VIO (Visual-Inertial Odometry).

These approaches enable GNSS-independent operations, ensuring continuity in indoor applications.

Visual Odometry (VIO), SLAM, and Perception Fusion

VIO (Visual-Inertial Odometry) estimates a drone's position by fusing visual streams from cameras with IMU (Inertial Measurement Unit) data. Visual features (e.g., corners or edges) are tracked over time, combined with IMU data to compute 3D positional changes.

SLAM (Simultaneous Localization and Mapping) enables simultaneous environmental mapping and self-positioning on that map. Visual, LiDAR, or radar-based SLAM methods sustain positional awareness in GPS-denied settings within swarms.

In multi-drone systems, individual maps are fused via sensor fusion algorithms, yielding a shared "common environmental model."

This process employs Kalman filters, particle filters, or federated filtering techniques. Consequently, each unit refines its position estimate using not only local perceptions but also data from neighbors, enhancing overall reliability.

Sensors: IMU, Cameras, LiDAR, and Depth Detectors

A swarm drone's environmental comprehension correlates directly with its sensors' type and quality.

Primary sensor types include:

- IMU (Inertial Measurement Unit): Measures velocity, acceleration, and angular rates; essential for short-term motion prediction.
- Camera Systems: RGB, stereo, or depth cameras support navigation and object recognition.

- LiDAR (Light Detection and Ranging): Scans environments via laser pulses for high-precision 3D maps; effective for obstacle detection and terrain modeling.
- ToF (Time-of-Flight) Sensors: Gauge distances by light pulse reflection time; used in close-range collision avoidance.

Modern swarm systems integrate these for multi-modal perception, providing resilience to sensor failures while allowing complementary data streams.

Common Reference Frames and Calibration

Successful swarm coordination requires interpreting measurement data within a shared reference frame.

Typically, three reference types are used:

1. Global reference (GNSS-based coordinates),

2. Local reference (relative positions from origin),

3. Virtual reference (coordinates defined relative to swarm center or leader drones).

Calibration is vital for frame consistency. In multi-sensor integration (e.g., camera-LiDAR alignment), minor errors can destabilize formations.

Thus, swarm systems employ pre-flight auto-calibration algorithms for alignment.

Formation and Motion Control

In swarm drone systems, formation and motion control constitutes the control mechanism enabling units to move coordinately within a specified geometric arrangement.

This structure preserves the visual and functional integrity of swarm behavior, directly influencing mission success. Formation control encompasses not only geometric alignment but also dynamic synchronization, stability, collision safety, and adaptability.,

Leader-Follower and Virtual Structure Approaches

The two most prevalent models in formation control literature are leader-follower and virtual structure approaches.

- Leader-Follower Approach: In this method, one or more drones are designated as “leaders”; the others track the leader’s motion. The leader’s position, velocity, and orientation data are relayed to followers. This architecture is computationally simple and operates with low latency in real-time applications. However, leader failure may compromise system integrity, necessitating dynamic leader assignment or redundancy mechanisms.

- Virtual Structure Approach: Here, the swarm is conceptualized as a rigid virtual entity, with each drone assigned to a point within this structure. The system thus behaves as a single cohesive body; motions and rotations are computed relative to the virtual structure's geometric center. This method proves highly effective for symmetric formations (e.g., triangles, circles, grids). Its drawbacks include high computational cost and stringent coordination demands.

In practice, these methods are often hybridized: the leader dictates the virtual structure's direction, while followers maintain alignment via local rules.

Collision Avoidance and Obstacle Evasion Strategies

Ensuring safe motion in swarm drones without disrupting formation stability requires critical collision avoidance mechanisms.

These strategies operate at three primary levels:

1. Local reactive avoidance: Drones detect nearby obstacles via sensors and generate repulsive forces based on potential field principles, enabling preemptive directional changes.

2. Predictive avoidance: Motion models predict trajectories from neighbors' velocity and acceleration data, anticipating collision risks temporally.

3. Rule-based avoidance: Analogous to traffic logic, priorities are defined for specific scenarios (e.g., directional or payload precedence).

Most employ potential fields, artificial force fields, or model predictive control (MPC) algorithms. The objective is to sustain swarm integrity while allowing individual safe navigation.

Obstacle Evasion and Dynamic Reconfiguration

In real-world missions, swarm drones frequently encounter unforeseen obstacles, activating dynamic reconfiguration capabilities.

This enables transitions between formations or circumvention and realignment around obstacles. For example, upon encountering a wall, the swarm may split into subgroups to navigate around it before recombining. Such behaviors are typically coordinated via graph-based adaptation or decentralized decision networks.

Drones update neighborhood matrices upon detecting environmental changes, reshaping swarm topology in real time.

Additionally, post-failure reconfiguration is vital: if a drone fails, remaining units redistribute tasks and optimize positions to fill gaps.

This process leverages Laplacian-based consensus control and distributed task allocation algorithms.

Multi-Target Tracking and Swarm Maneuvers

In certain missions, swarms must track multiple targets simultaneously, partitioning into subgroups for each.

Coordination is maintained through multi-task assignment and dynamic clustering techniques. During swarm maneuvers (e.g., turns, narrow passage traversal, or takeoff-landing choreography), temporal synchronization is paramount.

This is executed via distributed synchronization protocols, ensuring holistic motion that is aesthetic, balanced, and secure.

Task Planning and Allocation

In swarm drone systems, task planning and allocation defines the decision process determining which unit undertakes which task, when, and how toward a common objective.

This process lies at the core of the system's autonomous capacity. Allocation efficiency directly determines workload balance, energy consumption, task duration, and overall success.

Planning mechanisms typically integrate distributed optimization, game theory, market-based methods, and reinforcement learning approaches.

Market (Auction)-Based Task Allocation

Market-based task allocation treats each drone as a "bidder," distributing tasks via auction-like processes.

Each drone submits bids for tasks based on factors like energy status, position, payload capacity, or sensor capabilities.

A task manager (or central decision unit) evaluates bids and assigns the optimal candidate.

This model's primary advantages are computational efficiency and scalability. As task numbers increase, the system distributes them rapidly without a central planner.

However, limitations arise in dynamic environments requiring bid revisions. Modern systems employ dynamic auction algorithms, restarting bidding upon task changes.

Optimization-Based Planning (MIP, Graph Search, and Heuristic Approaches)

Swarm task planning is mathematically modeled as mixed-integer programming (MIP) or graph-based search problems.

The objective is organizing unit tasks to minimize energy, distance, time, and risk.

For instance, in area scanning, routes minimize total flight time while maximizing coverage.

As these are NP-hard, real-time applications favor approximate solutions (heuristic algorithms).

Popular approaches include:

- Genetic algorithms,
- Ant colony optimization (ACO),
- Particle swarm optimization (PSO),
- Tabu search.

These yield fast, satisfactory solutions in complex task spaces and align naturally with swarm structures via distributed processing and adaptation.

Multi-Agent Reinforcement Learning (MARL)

Advancing AI enables integration of learning-based approaches into swarm task planning.

MARL allows each drone to learn from experiences, developing system-level coordinated behaviors.

Drones interact with the environment, optimizing future actions via reward/penalty signals.

In exploration, drones learn to compete for uncovered areas while collaborating to boost coverage.

MARL’s key advantage is developing optimal strategies in complex environments without predefined models.

Challenges include credit assignment—attributing success to specific decisions. Solutions propose central training-decentralized execution (CTDE) or federated learning hybrids.

Thus, drones make locally and globally informed decisions for swarm-scale coordination.

Dynamic Task Redistribution

In real-world applications, conditions vary: targets shift, drones fail, or communications drop.

Dynamic redistribution ensures operational continuity.

This occurs in two stages:

1. Situational awareness: Analyze current tasks, energy levels, and environmental changes.

2. Reallocation: Transfer tasks from idle/overloaded drones to suitable candidates.

Adaptive optimization algorithms are used, such as Laplacian-based rebalancing or game-theoretic sharing.

The goal: Minimize energy and duration without compromising success.

Edge AI and Computing

In swarm drone systems, edge artificial intelligence (Edge AI) constitutes a computing approach enabling decision-making processes directly on the drone during flight.

Unlike classical centralized processing models, Edge AI architecture processes sensor data locally without cloud transmission, thereby reducing latency, eliminating connectivity dependency, and facilitating real-time responsiveness.

This structure represents one of the most effective means to enhance autonomy in swarm drones.

On-Board (Edge) Inference and Hardware Platforms

At the heart of Edge AI systems lies the on-board inference mechanism operating directly on the drone.

This mechanism executes tasks such as image processing, target recognition, path prediction, or collision avoidance in the field.

Hardware employed typically features high-performance embedded processors, GPUs, or NPUs (Neural Processing Units).

Popular platforms include the NVIDIA Jetson series, Intel Movidius, Google Coral, and Qualcomm Flight kits.

These boards enable seamless integration of deep learning models into the flight control loop.

For instance, a drone processes its image stream on-board to detect a target, then relays maneuver commands to the control system—all within milliseconds, sans central servers.

This setup offers substantial benefits for offline tasks, allowing swarms to operate independently in remote areas or under constrained radio communications.

Model Compression: Quantization, Pruning, and Transfer Learning

Given the limited processing power and energy capacity of edge devices, AI models require lightweighting.

Three primary methods predominate:

1. Quantization: Representing weights and activations at 8-bit or lower resolution instead of 32-bit to reduce computational load.
2. Pruning: Removing insignificant neurons or connections, thereby decreasing parameter count and processing time.
3. Transfer Learning: Fine-tuning pre-trained models on small datasets for swarm-specific tasks.

These techniques enable deep learning detection models (e.g., YOLO, MobileNet, EfficientNet) to operate with lower energy and higher efficiency in swarm systems.

Thus, each drone preserves its "local intelligence" while contributing to collective swarm behavior.

Vision Pipeline and Distributed Processing

In swarm drones, the vision pipeline denotes the workflow transforming raw sensor data into actionable insights.

This process typically comprises three stages:

1. Pre-processing: Noise reduction, contrast adjustment, color correction.
2. Feature extraction: Detection of visual or deep features.
3. Inference: Classification of detected objects/events and conversion to actions.

In swarm systems, this pipeline can operate distributively across units.

For example, one drone processes imagery while another performs depth analysis on the same feed; results fuse via low-latency network links.

This balances computational load and fosters collective cognition across the swarm.

Cloud-Edge Division of Labor and Hybrid Computing

Although Edge AI emphasizes local processing, certain tasks still leverage cloud computational power.

Thus, modern swarm systems adopt hybrid computing models:

- Edge Layer: Real-time operations like instantaneous decisions, collision avoidance, and path optimization occur here.
- Cloud Layer: High-compute tasks such as model training, map fusion, or task optimization are handled remotely.

This division balances loads while curbing energy use.

Data flow between edge and cloud is managed via asynchronous protocols and QoS-based prioritization.

Consequently, swarms can function offline independently or ingest updated intelligence from central sources when online.

Energy and Resource Management

In swarm drone systems, energy and resource management directly determines mission duration, coverage, and operational reliability.

Given the limited energy, processing power, and communication capacity of each drone, system-wide optimization is critical.

In this context, balancing energy consumption, equitably distributing task loads, and preserving swarm integrity are achievable through effective management strategies.

Battery Budget and Endurance Optimization

Drone energy consumption largely depends on flight maneuvers, communication traffic, and payload capacity.

The battery budget concept denotes the total energy allocatable to a drone for a given task. Accurate budgeting is essential for successful planning.

Optimization typically employs two core strategies:

1. Trajectory-based optimization: Routes are recalculated to minimize energy use, incorporating models for altitude and wind variations to extend flight endurance.

2. Task-based adaptation: As battery levels decline, drones transfer loads or responsibilities to neighbors, integrated with dynamic task redistribution.

Modern swarm systems use energy monitoring sensors to analyze real-time consumption profiles via central or distributed algorithms, enabling predictive power management through early loss forecasting.

Payload-Performance Balance

One of the primary factors influencing energy efficiency is the drone's payload weight.

As cameras, LiDAR, communication modules, or other equipment increase mass, thrust requirements rise, proportionally elevating consumption.

Thus, payload-performance balance must be meticulously managed in system design.

In practice, this is maintained via:

- Adaptive speed control: Dynamically adjusting speed profiles based on task priority.
- Modular payload systems: Mounting only necessary sensors or hardware per mission.
- Load sharing models: Distributing heavy tasks among swarm members.

This homogenizes swarm-wide energy use and extends mission duration.

Fault Tolerance and Mission Continuity

Energy management interlinks not only with optimization but also system resilience (fault tolerance).

A drone's energy depletion or failure should not degrade overall performance.

To this end, a three-stage fault tolerance mechanism is typically implemented:

1. Early warning: Drones broadcast alerts within the swarm when battery levels fall below thresholds.
2 Task transfer: Low-energy drones offload tasks to nearest neighbors via optimization algorithms selecting candidates based on energy and distance.
3. Formation correction: Post-transfer, formations auto-rebalance, reassigning positions for missing units.

This structure ensures resistance to gradual degradation; even with a depleted drone offline, the swarm sustains operations.

Swarm-Level Resource Sharing and Collective Management

Swarm-level energy and resource sharing aims to compensate for individual limitations collectively.

Resources like communication relays, processing power, and sensor data can be shared communally.

For example, a drone may serve as a relay node to bolster others' connectivity or assume distributed processing roles.

Such scenarios are supported by cooperative energy management or shared resource scheduling models.

Additionally, emerging systems experimentally employ power beaming or in-flight wireless recharging to maintain integrity.

Long-term, the goal is evolving swarms into autonomous energy ecosystems capable of self-optimizing sharing and planning.

Software Stack and Development Tools

The success of swarm drone systems hinges not only on hardware design but also on the modularity and reliability of the software architecture.

Control algorithms, communication protocols, perception-decision loops, and testing infrastructure for each drone in the swarm are executed via this stack.

This layer serves as the central element dictating both individual autonomous behaviors and collective coordination.

Modern swarm software typically revolves around open-source flight control platforms, robotic operating systems (ROS), and simulation tools.

The building blocks are detailed below.

PX4 and ArduPilot Ecosystems

The most prevalent flight control software in swarm drones are the PX4 and ArduPilot ecosystems.

Both open-source, they support diverse hardware platforms and offer adaptable architectures for swarm systems.

- PX4: A C++-based flight control software with high modularity. It executes real-time control loops and communicates via MAVLink protocol. PX4's microkernel architecture allows control modules (e.g., position, velocity, orientation) to run in separate threads per drone. This provides fault isolation and reliability in distributed swarm scenarios.

- ArduPilot: Features broader sensor support and accommodates fixed-wing, rotary-wing, and hybrid vehicles. Its advantages include ease of parameter tuning and rapid adaptation to varied mission profiles. Modules for energy optimization or payload management are user-customizable.

These ecosystems often integrate with ROS-based upper layers to form modular architectures in swarm operations.

ROS 2, MAVSDK, and Interface Layer

ROS 2 (Robot Operating System 2) is a foundational software infrastructure for managing distributed decision-making, data exchange, and task coordination in swarm drones.

Its DDS (Data Distribution Service)-based communication model ensures secure, synchronized data sharing among drones.

In ROS 2-based swarm architectures:

- Nodes: Represent functional components on each drone.
- Topics: Data channels for publishing sensor data, task statuses, or control commands.
- Services: Handle bidirectional request-response interactions.

Additionally, MAVSDK (MAVLink Software Development Kit) bridges MAVLink to ROS 2.

This enables high-level control commands (e.g., "maintain formation," "switch task," "report energy level") from ROS applications directly to swarm drones.

The interface layer enhances system flexibility while offering developers high-level abstraction for programming.

Simulation: Gazebo, AirSim, and Crazyswarm

Given the cost and risk of real-flight tests, simulation environments play a pivotal role in swarm development.

Algorithms' safety, formation stability, and network behaviors are validated pre-flight.

- Gazebo: Integrates natively with ROS and simulates realistic flight dynamics via physics engines (ODE, Bullet, DART). Developers can incorporate environmental factors like wind, obstacles, or sensor noise for authentic scenarios.
- AirSim (Microsoft): Delivers high-fidelity visual simulation, preferred for testing computer vision and deep learning tasks. It excels in generating training data for Edge AI systems.
- Crazyswarm 2: Tailored for small-scale micro-drones (e.g., Crazyflie), simulating real-time formation control and synchronized flight choreographies.

These tools are indispensable for testing swarm scalability and detecting algorithm flaws in safe settings.

HIL/SIL Testing Infrastructure

HIL (Hardware-in-the-Loop) and SIL (Software-in-the-Loop) tests validate real-system behaviors securely during development.

- SIL: Executes only software components in virtual environments, interacting control algorithms with sensor simulations.
- HIL: Tests actual hardware (e.g., flight controllers, sensor boards) alongside simulations, measuring real-time response times and interface stability.

These infrastructures enable safe swarm-scale updates and software release verification.

Parameters like energy consumption, processing load, and network latency can be analyzed in detail during tests.

Hardware Architecture and Platform Selection

Hardware architecture in swarm drone systems constitutes one of the foundational components determining mission performance and system stability.

Design influences not only flight performance but also energy management, communication efficiency, payload capacity, and maintenance ease.

Thus, hardware architecture must be considered alongside software and optimized per mission requirements.

Micro-Swarms and Field-Scale Platforms

Swarm drones generally divide into two categories: micro-swarms and field-scale platforms.

Each differs significantly in size, weight, sensor capabilities, and energy capacity.

- Micro-swarms: Comprise small drones (e.g., 100–300 grams). Suited for lab tests, indoor formation flights, and demonstrations. Low cost enables large swarms, but limited energy yields 5–10 minute flights. Optical tracking or UWB localization is preferred.

- Field-scale platforms: Feature higher battery capacity and advanced sensor integration. Carry external payloads for long-range missions. Ideal for agriculture, search-and-rescue, and industrial surveillance. Typically equipped with carbon fiber frames, high-thrust propellers, and multi-band GNSS modules.

These distinctions directly impact swarm scalability and energy strategy design.

Flight Controllers and Sensor Selection

Flight controllers represent the swarm's "neural core," processing IMU data to generate motor signals for stable flight.

Common types in swarm applications:

- Pixhawk series: Open-source, PX4/ArduPilot-compatible with broad community support.

- Crazyflie 2.x: Compact, low-latency for micro-swarms.

- DIY boards: Microcontroller-based (STM32, ESP32) optimized for custom tasks.

Sensor selection hinges on mission:

- RGB/depth cameras for visual tasks,

- IMU + GNSS/UWB for positioning,

- LiDAR/stereo cameras for mapping,

- Ultrasonic/ToF for collision avoidance.

Integration must balance weight-energy; excess sensors shorten flight time.

Communication Hardware and Antenna Design

Communication hardware forms the primary physical layer preserving network integrity.

Modules include Wi-Fi, ZigBee, LoRa, UWB, or LTE, selected by swarm size, range, and data volume.

- Wi-Fi: For short-range, high-bandwidth; high energy draw.
- LoRa (Long Range): For low-data-rate, long-range; effective for status reporting.
- UWB: Dual-use for positioning/communication; low latency for formation control.

Antenna design affects reliability. Omnidirectional antennas suit swarms; directional reduce interference in large ones.Emerging research targets dynamic optimization via adaptive array antennas.

Modularity and Maintenance Ease

High drone counts complicate maintenance; thus, hardware should follow modular design principles.

Modularity eases component swaps (e.g., motors, sensors, controllers) upon failure.

Standard interfaces (USB-C, JST, XT60) reduce downtime and enhance compatibility.

Advanced swarms employ automated stations (e.g., autonomous battery swaps, wireless charging).

These sequentially charge drones or apply firmware updates wirelessly, minimizing human intervention.

Safety, Security, and Cybersecurity

In swarm drone systems, safety and security encompass not only hardware resilience but also communication integrity, cyber protection mechanisms, and operational risk management.

The complex, distributed architecture creates a larger attack surface than individual drones. Thus, swarm systems require multilayered protection strategies for both physical safety and cybersecurity.

This section presents a holistic security framework, spanning safety procedures, attack prevention, threat modeling, and certification processes.

Safety Framework and Emergency Procedures

Safety management in swarm operations is built on risk mitigation and damage control principles.

Each drone must be designed to protect both itself and swarm integrity.

Safety systems typically operate at three levels:

1. Flight safety: The system enters "failsafe" mode upon anomalous acceleration, altitude, or orientation data.

2. Mission safety: Drones auto-return or land upon breaching geofences.

3. Swarm safety: Deviant units (e.g., generating erroneous commands) are isolated.

Emergency procedures (e.g., link loss, battery failure, rotor damage) must be embedded in software.

Modern swarms incorporate automated emergency landings or self-disbanding protocols.

Safe Landing and Separation Scenarios

In multi-drone operations, one rogue unit risks cascading failures across the swarm.

Safe separation strategies thus employ mathematical models ensuring minimum distances.

Typical separation steps:

- Faulty/unresponsive drones are flagged via network "isolation signals."
- Neighbors apply repulsive potential fields for distancing.
- Isolated units perform controlled landings or are expelled.

This synchronizes via consensus mechanisms, preserving overall formation.

GPS Spoofing, Link Hijacking, and Jamming Resilience

Cybersecurity threats to swarm drones can be more insidious than physical risks.

Common attacks include:

- GPS spoofing: Attackers broadcast fake signals to mislead positioning. Countermeasures involve multi-sensor fusion (e.g., IMU + VIO) and GNSS anomaly detection algorithms for statistical outlier identification.
- Link hijacking: Intruders mimic channels to inject commands. End-to-end encryption and certificate-based authentication mitigate this.
- Jamming: Prevalent in military contexts. Drones detect interference and switch to frequency-hopping spread spectrum (FHSS) communication.

These enhance resilience, sustaining intra-swarm communication security.

Certification, Compliance, and FMEA Analyses

Swarm systems require safety certifications and compliance standards for civilian/industrial use.

FMEA (Failure Mode and Effects Analysis) systematically evaluates failure modes and their swarm impacts to preemptively minimize risks.

Internationally, EASA and FAA regulate BVLOS operations, mandating hardware reliability, connectivity continuity, and software safety tests.

These standards render swarm drones technologically and legally sustainable.

Regulations and Standards

The proliferation of swarm drone technology necessitates not only technical advancements but also aligned legal and regulatory frameworks.

Simultaneous operations of multiple autonomous aerial vehicles in shared airspace raise novel issues in safety, privacy, and air traffic management.

Thus, national civil aviation authorities and international bodies are developing specific regulations and certification standards for safe swarm integration.

National Regulations (e.g., Turkey – SHT-UAV)

In Turkey, the legal framework for unmanned aerial vehicles is defined by the SHT-UAV Directive issued by the Directorate General of Civil Aviation (DGCA).

This regulation outlines UAV classification, pilot licensing, flight permissions, and operational limits.

Although provisions for swarm drones are not explicitly stated, general UAV rules apply bindingly.

Key principles under SHT-UAV relevant to swarm operations include:

- Mandatory registration of all drones with identification plates (ID).
- Operations within visual line of sight (VLOS); special permissions required for beyond visual line of sight (BVLOS).
- Consideration of air traffic density, populated areas, and safety constraints in operational zones.

Future DGCA regulations specifically for swarm operations are anticipated, defining collective permissions, shared central responsibilities, and automated identification.

International Frameworks: EASA, FAA, and BVLOS Operations

In Europe and the US, regulatory frameworks for swarm drones are managed by EASA (European Union Aviation Safety Agency) and FAA (Federal Aviation Administration), respectively.

- EASA Regulations: European UAV operations are categorized into "open," "specific," and "certified" risk levels. Swarm operations typically fall under "specific," mandating risk assessment (SORA – Specific Operations Risk Assessment). This evaluates factors like swarm size, flight range, communication structure, and autonomy level.

- FAA Regulations: Based on FAA Part 107 ruleset. BVLOS missions require special waivers. FAA mandates Remote ID; each drone broadcasts identity and position data. This directly relates to swarm identification infrastructure.

BVLOS regulations enable autonomous wide-area swarm operations while requiring communication security and central oversight.

Identification, U-Space, and UTM Systems

Integrating swarm drone technology into airspace demands cohesive identification and traffic management systems.

Two primary concepts emerge: U-Space (Europe) and UTM (Unmanned Traffic Management, US).

- U-Space: Developed by the European Commission, this framework provides digital service layers for safe low-altitude drone operations. Layers cover authentication, dynamic airspace access, collision avoidance, and monitoring.

- UTM: A FAA-NASA collaboration aiming for safe shared airspace operations of autonomous/semi-autonomous drones. UTM centrally monitors swarms, logging real-time position, identity, and task status per drone.

These structures will enable future mixed airspace integration with manned aircraft.

Data Protection, Privacy, and Ethical Dimensions

Swarm drones collect vast visual, positional, and environmental data, posing ethical data security and privacy challenges.

Collected data must be safeguarded against unauthorized access, with personal data anonymized and storage policies clearly defined.

The EU's GDPR (General Data Protection Regulation) serves as a global reference.

In swarm systems, data processing follows principles such as:

- Data minimization: Collecting only mission-essential data,
- Local processing (edge processing): Handling sensitive data on-device without cloud transfer,
- Anonymous identification: Assigning identifiers unlinkable to actual user identities.

Ethically, prioritizing human oversight, transparent decision mechanisms, and minimized environmental impacts is essential.

Experimental Design, Validation, and Metrics (Field Test Plan and Incremental Scaling Approach)

Swarm drone system testing follows an incremental scaling principle.

The goal is validating stability in low-risk settings (simulations, indoor tests) before progressing to open-field and multi-agent scenarios.

This process typically unfolds in four stages:

1. Simulation validation: Control algorithms, protocols, and failure scenarios tested virtually.
2. Indoor testing: Micro-swarms assess stability, sensor fusion, and formation control in real time.
3. Small-scale field testing: 3–5 drones execute short-range tasks; analyze link latency, data loss, battery endurance.
4. Full-scale field trials: Measure collective behavior under realistic missions (e.g., search-and-rescue, agricultural monitoring).

This approach controls risks while adapting algorithms to real-world conditions.

Performance Metrics (Coverage, Response, Reliability)

Swarm performance metrics divide into three categories: spatial efficiency, dynamic response, and operational reliability.

- Coverage Ratio: Measures task area scanned/covered, expressed as percentage. Primary for exploration/mapping.
- Response Time: Duration for rebalancing after new commands or environmental changes. Indicates rapid adaptation.

- Reliability: Error-free task sustainment rate over time, factoring hardware failures and link disruptions.

Secondary metrics include energy efficiency, formation stability, data loss rate, and uptime.

Stress Testing and Edge Cases

Stress tests evaluate resilience under extremes (high winds, signal loss, jamming, battery depletion, sensor faults).

Typical scenarios:

- Communication outage: Intentionally disconnect units; measure reconfiguration time.
- Formation disruption: Induce positional errors in one unit; test auto-realignment.- Energy imbalance: Deplete one drone's battery; monitor task reassignment response.

These ensure functionality beyond ideals, often using Monte Carlo simulations or probabilistic failure modeling

Reproducibility, Data Collection, and Reporting

Scientific validity demands repeatable experiments, requiring integrated logging and control at software/hardware levels.

Key elements:

- Timestamped logs: Sensors, commands, messages tagged temporally.
- Unified data format: Consistent structures (e.g., ROS bag files).
- Automated error reporting: Tag/classify anomalies.
- Version control: Track changes (e.g., Git).

These enable replication across groups, supporting reproducibility in swarm technologies.

Case Studies

The practical impact of swarm drone technology becomes evident not solely through theoretical models or laboratory experiments but through real-world application examples.

This section focuses on four core scenarios representing swarm drones' deployment across sectors: disaster management, agriculture, industrial inspection, and entertainment displays.

Each subsection examines system architecture, task structure, and achieved benefits from a unique perspective.

Disaster and Search-and-Rescue Swarms

In post-disaster search-and-rescue operations, time is a critical variable; rapid access to information holds life-saving potential.

Swarm drones in search missions aim to scan vast areas in parallel and coordinated fashion.

In such systems, each drone covers a designated sub-region, shares detection results via local networks, and relays suspicious signals (e.g., heat, sound, motion) to the swarm hub.

Techniques employed include thermal cameras, acoustic sensors, and VIO-based local mapping.

A drone with depleting energy autonomously returns to base, while remaining units dynamically fill the gap—demonstrating the system's seamless mission continuity.

This approach proved effective in experimental projects following the 2023 Turkey and 2021 Haiti earthquakes, scanning narrow areas inaccessible to human teams.

In the future, such swarms could integrate with disaster intelligence centers to form real-time decision-support systems.

Agriculture, Precision Spraying, and Monitoring Applications

In agricultural technologies, swarm drones represent one of the most advanced components of precision agriculture.

Multiple drones can simultaneously survey expansive fields, perform plant health analyses, and autonomously distribute fertilizer or pesticide spraying tasks.

Core technologies utilized include:

- NDVI (Normalized Difference Vegetation Index) analyses for mapping plant stress,
- Multispectral camera systems for detecting crop density,
- Task allocation algorithms assigning drones to distinct parcels.

The swarm-based method can reduce mission duration by up to 60% compared to single-drone approaches.

Moreover, drones dynamically adjust positions and spraying intensity relative to each other for uniform coverage.

These systems align directly with sustainable agriculture's goals of resource efficiency and environmental sensitivity.

Industrial Inspection and Inventory Management

Swarm drones serve as efficiency enhancers in repetitive observation and maintenance tasks at industrial facilities.

Particularly in refineries, power plants, ports, and large warehouses, swarm operations boost coverage while shortening durations.

Architectures typically adopt semi-decentralized designs: each drone operates autonomously on its route but periodically synchronizes with a central controller.

Visual inspections employ thermal cameras and high-resolution imaging modules for anomaly detection.

For instance, in an energy facility, the swarm monitors temperature variances to identify potential failures early.

Similarly, in warehouses, drones conduct stock counts via RFID scanning.

These systems reduce human involvement while yielding significant improvements in occupational safety and process speed.

Displays, Light Shows, and Coordination Systems

One of swarm drones' most visible applications is light shows.

In these performances, hundreds or thousands of drones execute synchronized flights to form pre-planned formations.

Each drone's LED lighting system activates varied colors and patterns at precise intervals, creating three-dimensional aerial compositions.

Such systems demand high temporal synchronization, GPS precision, and intersection avoidance algorithms.

Swarm choreography typically employs a two-layered software structure:

1. Planning layer: Predefines formation geometries and transition paths.

2. Real-time control layer: Continuously monitors each drone's position for immediate deviation corrections.

These displays serve not only artistic purposes but also as laboratories for testing swarm control algorithm scalability.

Currently, some technology firms promote such shows as energy-efficient and zero-carbon events.

Design Patterns and Best Practices

The intricate nature of swarm drone systems necessitates design patterns beyond traditional engineering approaches.

These patterns offer reusable solutions to recurring design challenges across swarm systems.

This section presents four most effective design patterns for swarm drones and their practical implementation principles.

Swarm Initialization, Landing, and Takeoff Choreography

Safely initiating and concluding swarm operations is pivotal for system integrity.

A minor coordination error during takeoff could trigger cascading collisions.

Thus, swarms employ choreographic takeoff-landing patterns.

This pattern rests on three core principles:

1. Staggered launch: Drones ascend in sequence with delays, each awaiting the prior's completion.

2. Area allocation: Pre-assigned takeoff points verified via GNSS.

3. Safe landing zones: During descent, drones shift to individual modes with auto-partitioned areas.

This method enhances safety in high-density flights like light shows or field tests.

Algorithms can further prioritize landing sequences for low-battery drones.

Robust Communication Architectural Patterns

Swarm success hinges on communication infrastructure resilience.

Hence, patterns like redundant mesh and failover routing are applied at the communication layer.

- Redundant mesh pattern: Each drone maintains multiple neighbor links, ensuring information flow via alternatives upon failures.
- Failover routing pattern: Upon detection of loss, drones auto-switch protocols (e.g., Wi-Fi to LoRa), preventing data loss.

Additionally, layered networking segregates task control messages, telemetry, and media streams into distinct channels.

This facilitates QoS management and bolsters overall stability.

Heterogeneous Task Ecosystem

Modern swarms may comprise units with varying hardware or functions.

This heterogeneous structure enhances flexibility but complicates coordination.

The employed design pattern is “role-based task allocation.”

Each drone is assigned a role based on capabilities—e.g.:

- Observer (camera, LiDAR),
- Communication relay (network amplifier),
- Carrier (payload transporter),
- Decision unit (Edge AI-equipped).

The planning layer manages roles through resource-aware models.

Heterogeneous swarms also feature modular software components (e.g., ROS nodes) auto-adaptable to diverse hardware.

This approach amplifies task diversity while simplifying maintenance and updates.

Operational Manual and Standard Operating Procedures (SOP)

Secure and consistent swarm operations require operational discipline alongside technical design.

Standard Operating Procedures (SOP) ensure field personnel execute tasks error-free.

SOP documents typically include:

- Pre-takeoff checklist (battery status, connectivity test, software version),

- In-flight monitoring protocols (telemetry oversight, swarm synchronization),
- Emergency procedures (lost drone, signal interruption, forced landing),
- Post-mission data collection and reporting processes.

Integrating SOP with software minimizes human error.

For instance, some control software disables activation until digital checklists are completed.

Such "embedded safety" designs ensure professional-standard swarm operations.

Open Problems and Research Directions

Swarm drone systems have achieved significant technological maturity over the past decade; however, numerous open research challenges persist at both theoretical and applied levels.

These issues typically cluster under three core headings: scalability, reliable autonomy, and human-system interaction.

This section structures future research directions for swarm drones in an original framework.

Management of Very Large-Scale (100+ Drone) Systems

Most swarm applications to date have been limited to 10–50 drones.

Next-generation systems target simultaneous operation of hundreds or thousands of units.

This scale introduces novel challenges in scalable control and communication coordination.

Key research topics include:

- Distributed decision-making complexity: Consensus algorithms' convergence times elongate with increasing drone counts.
- Network density management: Data collisions and delays reach critical levels in 100+ unit swarms.
- Hierarchical control structures: Swarms partitioned into subgroups (e.g., clusters) managed via local decision units.

Research emphasizes the "swarm-of-swarms" concept, fostering multi-layered coordination models.

This reduces computational load while facilitating fault isolation.

Fully GPS-Denied and Dark Environment Swarms

Swarm systems operable in GPS-absent or weak-signal areas (e.g., underground, indoors, tunnels, forests) represent one of today's most active research domains.

In such environments, swarms rely entirely on perception-based localization methods.

Developed approaches include:

- Visual-inertial odometry (VIO): Fusing camera and IMU data for GPS-free motion tracking.
- Collaborative SLAM: Drones share and merge maps of the same environment.
- Light- or sound-based localization: Relative positioning via LED signals or acoustic echoes.

However, these incur high energy costs and accuracy sensitive to conditions.

Future research thus focuses on lightweight, robust sensor fusion architectures.

Human-Swarm Interaction (HRI/HSI)

In swarm drones, the human operator's role has shifted to strategic oversight.

Modern systems manage swarm behavior rather than individual units.

This paradigm evokes a new field: Human-Swarm Interaction (HSI) research.

Topics encompass:

- Natural interaction interfaces: Voice, gesture, or touch commands supplanting traditional joysticks.
- Situational awareness: Intuitive visualization systems for holistic operator comprehension of swarm dynamics.
- Trust-control balance: Dynamically delineating boundaries between human intervention and autonomous decisions.

Advancements here prove critical for human-robot teams and emergency coordination scenarios.

Autonomous Logistics and Smart Warehouse Swarms

The autonomous logistics paradigm with swarm drones constitutes an industrial transformation frontier.

Here, drones coordinate for intra-warehouse or inter-city material transport.

The aim: Fully automated supply chains sans human intervention.

Current research targets four primary challenges:

1. Navigation and collision avoidance: Dynamic route generation in confined spaces.
2. Payload balancing: Task sharing among varying-capacity drones.
3. Energy management: Autonomous charging or battery swaps within mission cycles.
4. AI-supported planning: MARL (Multi-Agent Reinforcement Learning) models for demand forecasting and route optimization.

Scalability of these systems could underpin unmanned warehouses and factories.

Experimental projects have successfully tested end-to-end autonomous delivery swarms in small-scale campuses or industrial zones.

Conclusion and Future Perspective

Swarm drone technology transcends mere engineering achievement; it exemplifies the tangible application of nature-inspired collective intelligence principles to engineering domains.

Positioned at the intersection of distributed systems, communication, artificial intelligence, and autonomy, this technology has forged a paradigm shaping contemporary robotics research.

The sections addressed herein—from theoretical foundations to software architectures, energy management to cybersecurity—delineate a multilayered systemic understanding of swarm drones.

Each layer functions as a complementary component enhancing the swarm's functionality, resilience, and environmental awareness.

Overall Evaluation

Swarm drones' efficacy crystallizes along four foundational axes:

1. Distributed decision-making: Collective coordination mechanisms supplanting centralized control augment system flexibility and fault tolerance.

2. Perceptual integration: Coalescence of diverse sensor data (cameras, IMUs, LiDAR, UWB) endows drones with environmental acuity.

3. AI-supported autonomy: Edge AI inference engines enable independent decisions at both individual and collective scales.

4. Sustainable operational infrastructure: Modular architectures in energy, networking, and maintenance facilitate long-term, scalable deployments.

Collectively, these elements elevate swarm systems beyond mere “flying robot collectives” into dynamic decision ecosystems.

Future Technological Trajectories

Over the next decade, swarm drone technology is poised to mature across three primary domains:

- Full autonomy and task awareness: Drones will contextualize mission objectives to devise targeted strategies, inaugurating an era of “goal-oriented swarm intelligence.”

- Adaptive network infrastructures: Integration of 6G and satellite-based networks will enable seamless global-scale swarm connectivity. This heralds trans-geographic swarm operations.

- Bio-inspired control algorithms: Novel models drawn from ant colonies, bird flocks, and fish schools will render swarm dynamics more stable and energy-efficient.

Concurrently, ethical and regulatory integrations must evolve in tandem with technical advances, as swarms’ societal visibility amplifies concerns over privacy, security, and environmental stewardship.

Strategic and Societal Implications

Swarm drones will emerge not only as technological but as strategic assets.

From disaster response to defense, agriculture to logistics, sectors are centering swarm intelligence in core processes.

This shift yields three strategic dividends:

- Enhanced situational awareness: Real-time data sharing accelerates decision cycles,

- Unmanned risk mitigation: Reduced human exposure in hazardous environments,
- Efficiency gains: Concurrent multitask execution with minimal energy.

Societally, adoption within frameworks of public trust, data privacy, and ethical autonomy will dictate this transformation's sustainability.

Forward Outlook

The evolution of swarm drone systems surpasses engineering—it manifests collective intelligence in the physical realm.

In the near future, swarms will mature into autonomous ecosystems managing self-sustaining energy networks, rendering contextually attuned decisions, and learning interdependently.

This vision signals a nascent technological epoch born from AI, network engineering, and cyber-physical systems convergence.

Ultimately, swarm drone technology transcends research confines to form the nucleus of tomorrow's autonomous infrastructures.

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Quality Control in the Apparel Industry: A Printing and Embroidery Perspective

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Introduction

The apparel industry constitutes one of the most critical segments of the textile value chain and holds strategic significance due to its high employment capacity, contribution to foreign trade, and impact on economic growth. Particularly in developing countries, the labor-intensive production structure of the sector provides extensive employment opportunities while also positioning it as a major production hub within global supply chains (Euratex, 2024). The global apparel industry is projected to grow at an average annual rate of approximately 4% by 2025, a trend that is expected to further intensify competition in the sector (Statista, 2024).

Turkey stands out as one of the leading countries in the global market with its production capacity and export strength in the apparel sector. In particular, strong trade relations established with the European Union countries position Turkey as a reliable partner within supply chains (International Trade Centre [ITC], 2024). Moreover, sustainable production practices, fast delivery capability, and flexible manufacturing structure are among the key factors enhancing Turkey's competitiveness. As of 2024, the apparel industry has held a significant share in Turkey's total exports, providing substantial foreign exchange earnings for the national economy (Turkish Exporters Assembly [TİM], 2024).

The concept of quality in the apparel sector is a determinant of a firm's competitiveness and is directly linked to consumer satisfaction, brand reputation, and cost efficiency.

Errors occurring during the production process lead to both product rejections and rework costs. Such quality-related issues increase product return rates, warranty expenses, and brand-associated losses. Therefore, quality control practices are of central importance for production efficiency and financial sustainability (Radmin, 2024).

With the rise of technology and automation, quality control practices are also transforming. Computer vision, machine learning, and artificial intelligence-based methods have the potential to reduce errors stemming from the limitations of human vision, particularly in areas such as early detection of fabric surface defects, monitoring of print alignment, and classification of embroidery flaws. These approaches enable the early identification of defects in production, thereby reducing the need for rework and minimizing waste rates, while simultaneously improving the speed and repeatability of quality control processes. However, when implementing technological solutions, technical challenges such as data infrastructure, standardization of cameras and lighting, determination of classification thresholds, and adaptation to field conditions must also be taken into account (Ozek et al., 2025).

This study aims to examine printing and embroidery processes in the apparel industry in detail and to identify the most common types of defects encountered in these processes in light of both literature and field practices. Issues such as dye bleeding, pattern misalignment, stencil clogging, and stains or creases on the fabric are the focal points in printing processes; while in embroidery, errors such as thread looping, pattern distortion, oil stains, and marking traces are emphasized. In conclusion, this study seeks to highlight the significance of printing and embroidery in terms of quality control within the apparel industry and to systematically present the types of defects observed in these areas.

Overview of the apparel industry

The apparel industry encompasses a wide value chain that includes both design and production processes. The production process typically begins with the procurement of raw materials. The selection of fabrics is determined by the type of product, its intended use, and the required quality standards. Procured fabrics are subjected to quality control tests before production and are stored under appropriate conditions. This stage is critical not only for production efficiency but also for the quality of the final product. Storage conditions necessitate careful management of factors such as humidity, light, and temperature.

Following the proper procurement of fabrics, the cutting process begins. This stage involves cutting the fabric according to the patterns of the product to be manufactured and can be performed manually or with automated machinery. The accuracy and precision of cutting directly influence both labor costs and product quality in subsequent stages. As one of the cornerstones of the production process, cutting must be carried out meticulously to ensure a defect-free product.

After the cutting stage, printing and embroidery processes are applied to enhance the aesthetic value of the product. Printing is commonly performed using screen printing, digital printing, or transfer printing techniques, while embroidery involves creating patterns with threads. The techniques employed at this stage vary depending on the target market and design specifications of the product. In modern apparel manufacturing, digital printing and computerized embroidery machines not only increase production speed but also support design diversity.

The sewing process ensures the assembly of the cut pieces and gives the product its final form. At this stage, workmanship quality, the machines used, and sewing techniques determine both the durability and the aesthetic appearance of the garment. Following sewing, the ironing process finalizes the shape and appearance of the product, preparing it for the packaging stage. Packaging represents the final step, encompassing the preparation and storage of products in a manner suitable for shipment.

In today's apparel industry, various technologies are employed to improve production processes and enhance efficiency. Automatic cutting machines, digital printing systems, robotic sewing machines, and smart manufacturing systems constitute the core components of modern production approaches. With the advent of Industry 4.0, data analytics, production planning, and quality control processes are becoming increasingly digitalized and optimized. These technological advancements not only strengthen competitiveness in the sector but also shorten production lead times and minimize errors (Sağbaş & Özdil, 2022).

Nevertheless, the challenges faced by the industry cannot be underestimated. Production costs are influenced by multiple factors such as raw material prices, labor expenses, and energy consumption. Rapidly changing consumer demands require production processes to be both flexible and responsive, which may pose difficulties in terms of production planning and supply chain management. The effectiveness of quality control processes is of critical importance for maintaining brands' competitive advantage and ensuring customer satisfaction. In addition, environmental impacts and sustainable manufacturing practices are becoming increasingly prominent in the sector. Sustainability is evaluated not only as a matter of environmental responsibility but also as a factor that enhances both economic value and brand reputation (Erdem & Doğan, 2020).

The Importance of Quality Control in the Apparel Industry

In the apparel industry, quality refers to the extent to which a product meets customer expectations. Consumers make purchasing decisions not only based on the aesthetic features of the product but also by considering elements such as durability, comfort, and functionality. Therefore, quality is directly related not only to the physical characteristics of the garment but also to the reliability of the brand and the level of customer satisfaction.

Quality control is a systematic set of activities carried out during the production process to ensure that products comply with predefined quality standards. This process begins with the procurement of raw materials and is applied at every stage of production as well as before the shipment of the final product. By enabling the early detection and correction of defects, quality control ensures the continuity of product quality and enhances customer satisfaction (Vaughn, 2022).

Critical Factors Affecting Quality

Fabric and Material Quality: The quality of fabrics and auxiliary materials used is one of the most fundamental factors determining both the durability and appearance of the apparel product. Key factors affecting the aesthetic value of the product include fabric surface smoothness, color consistency, shrinkage, and pilling tendency. Additionally, the selection of complementary materials such as linings, buttons, zippers, and sewing threads directly impacts the product's longevity. Therefore, careful evaluation of material quality at the initial stages of production is a critical step to ensure the overall quality of the garment.

Workmanship and Operator Skill: Workmanship quality plays a crucial role at every stage of the production process. The skills of operators, their ability to use machinery correctly, and their attention to detail directly influence product quality. A trained and experienced workforce reduces production errors and enhances efficiency.

Production Equipment and Technology: Modern production equipment and technologies increase both the speed and accuracy of the manufacturing process. Computer-aided systems and automated machinery reduce error rates in cutting and sewing operations while enhancing production capacity. These technologies also improve the effectiveness of quality control processes (Kumaş & Duru Baykal, 2023).

Types of Printing and Embroidery in the Apparel Industry

Types of Printing

There are numerous printing techniques used in the textile industry. This section discusses the printing methods commonly employed in the sector, as listed below:

- Water-Based Screen Printing
- Pigment Printing
- High-Relief Printing

- Embossed Printing
- Foil Printing
- Glitter Printing

Water-Based Screen Printing: In water-based printing, water-based inks are used, which possess organic characteristics due to their special compositions. Fabrics printed with water-based inks, which can be washed at 60°C, also offer higher elasticity compared to other printing methods (Keser, 2022). The environmental and human health friendliness of water-based screen-printing materials has made this technique a preferred method for both industrial and artistic applications (Esen & Gündoğdu, 2021).

Pigment Printing: Pigment printing is considered one of the oldest and most important printing techniques in the textile industry. The basic principle involves fixing colored pigments, which are insoluble in water and have no affinity to textile fibers, onto the fabric with the help of a chemical binder. Pigment printing is particularly favored for cotton fabrics (Orhan, 2010).

High-Relief Printing: High-relief printing is a technique in which the design to be printed has raised surfaces. Only the raised areas of the printing plate receive the ink, which penetrates the fabric during the printing process.

Embossed Printing: Embossed printing is a special technique that adds volume and a tactile effect to the fabric. It is achieved by transferring paste mixed with coloring agents onto the fabric using a mold and then fixing it to create a raised surface (Ateks Emprime, 2019). This method produces a pattern that is perceptible both visually and to the touch.

Foil Printing: Foil printing involves transferring metallic foil materials, such as gold, silver, or other metallic-looking foils, onto fabric or other surfaces.

Glitter Printing: Glitter printing is used in the textile industry to create an aesthetic effect. Glitter is added to an adhesive and applied to the fabric using a printing mold. This technique produces a bright and eye-catching visual appearance due to the reflective properties of the glitter.

Types of Embroidery

There are various types of embroidery used in the textile industry. This section addresses the embroidery techniques commonly employed in the sector, as listed below:

- Flat Embroidery
- 3D Embroidery
- Chain Stitch

- Satin Stitch
- Chenille Embroidery
- Goldwork Embroidery
- Cutwork Embroidery

Flat Embroidery: This is the most used machine embroidery type. The design is directly stitched onto the fabric surface, producing a flat and smooth pattern. It is generally preferred for logos, lettering, or simple motifs and is commonly applied on t-shirts, shirts, and jackets (Corbet, 2016).

3D Embroidery: A raised effect is achieved by placing a special foam under the design. This technique is typically used on caps, sweatshirts, and sportswear (Deer, 2025).

Chain Stitch: This type of stitch consists of interlinked loops. While it is common in traditional hand embroidery, it can now be executed with industrial machines. It is especially favored for ethnic patterns and lettering (TRC Leiden, 2017).

Satin Stitch: The interior of the design is filled with closely spaced parallel stitches. Although it resembles flat embroidery, it provides a shinier and more pronounced appearance. It is frequently used for logos and text embroidery (TRC Leiden, 2017).

Chenille Embroidery: This embroidery uses thick, velvety, and fuzzy threads, resulting in a soft and raised texture. It is particularly used for college jackets and sportswear (Wilcom, 2021).

Goldwork Embroidery: This decorative technique employs gold or silver metallic threads. It is typically used in luxury and ceremonial garments, particularly traditional and religious attire. The threads are usually made from metal wires plated with gold, silver, or copper, or from special metallic-looking threads. The metallic threads are not directly stitched onto the fabric; instead, they are laid on the surface and secured with various stitching techniques (Jones & Nabil, 2022).

Cutwork Embroidery: In this type of embroidery, specific sections of the fabric are cut out, and the surrounding areas are finished with embroidery stitches. It is an elegant technique that is particularly preferred in summer women's apparel and children's dresses (Mohapatra et al., 2015).

Factors Affecting Quality in Printing and Embroidery

Printing and embroidery processes are critical not only for the aesthetic appearance of apparel products but also for customer satisfaction and product longevity in the market.

The factors influencing quality in these processes depend on a wide range of variables, including material selection, technology, operator skill, and process parameters. These factors are examined in detail below.

Fabric and auxiliary material properties

The structural characteristics of the fabric—such as knit construction, type of yarn, surface smoothness, and fabric weight—are key variables determining print quality. For instance, a study by Tse and Briggs (1999) tested different knit structures and yarn thicknesses in cotton fabrics; these variables were found to significantly influence quality criteria such as line sharpness, color saturation, and surface texture.

Similarly, the quality of auxiliary materials plays a critical role in embroidery. A study conducted by Emekli and Bahadır Ünal (2019) examined the effects of lining types, upper and lower thread tension, machine settings, and fabric surface on embroidery quality. For example, using thick and heavy linings in large embroidery areas negatively impacted wearer comfort, whereas lighter and water- or heat-soluble linings were preferred for small areas such as logos.

Printing and embroidery process parameters

The type of dye or ink and the application parameters—such as the number of ink layers, fixation temperature, and post-printing treatments—directly affect print quality attributes, including durability and color fastness. For example, in the article "Textile Printing Combined with Embroidery", it was reported that increasing the number of ink layers in inkjet printing enhances resistance to light and washing; however, excessive layering may negatively affect the hand feel of the fabric and increase production costs (Stümer & Stümer, 2008). Additionally, evaluating prints through both visual and quantitative measurements is crucial. In the study by Tse and Briggs (1999), automated analysis systems were shown to objectively reveal the effects of fabric structure, yarn types, and pre-treatment processes on print quality.

During embroidery, the accuracy of machine settings significantly influences quality. Emekli and Bahadır Ünal (2019) found that improper selection of upper and lower thread tensions can lead to issues such as lower thread protrusion, pattern misalignment, or puffiness. The size and placement of the design are also important. While small logos may require different lining choices, large designs can encounter greater problems with bulk, weight, and surface stiffness. These factors must be considered in terms of both aesthetics and wearer comfort.

Visual perception and objective measurement

Quality assessment in printing and embroidery is often based on visual perception;

however, human factors such as operator fatigue and lighting conditions can compromise consistent evaluation. Therefore, objective measurement techniques are increasingly important. Digital image processing methods, as well as colorimetry assessments of contrast, optical density, and line sharpness, allow for more consistent and reliable analysis of quality (Kumari et al., 2021; Tse et al., 1999).

Causes of Printing and Embroidery Defects in the Apparel Industry

The increasing demand for high-quality products and rapidly changing economic conditions have made it even more critical for apparel manufacturers to produce items at the correct quality standards. Identifying sources of variability in the production process is essential to minimize defects and enhance process performance (Ersöz et al., 2021).

Printing defects

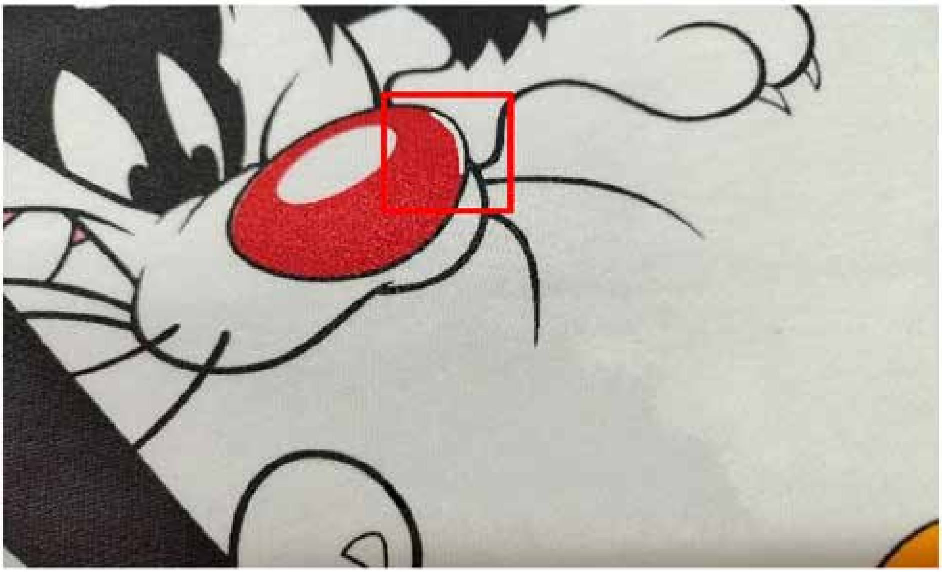
Stencil Defect: In screen printing, a "stencil defect" refers to a problem caused by damage to the stencil used during printing or improper preparation of the stencil. This defect can prevent the print from proceeding correctly and may manifest in various forms.

The primary causes of stencil defects include:

- Uneven application of the emulsion
- Errors in exposure time and incorrect exposure
- Improper placement of the stencil on the printing machine

Figure 1

Example of a "Stencil Defect"

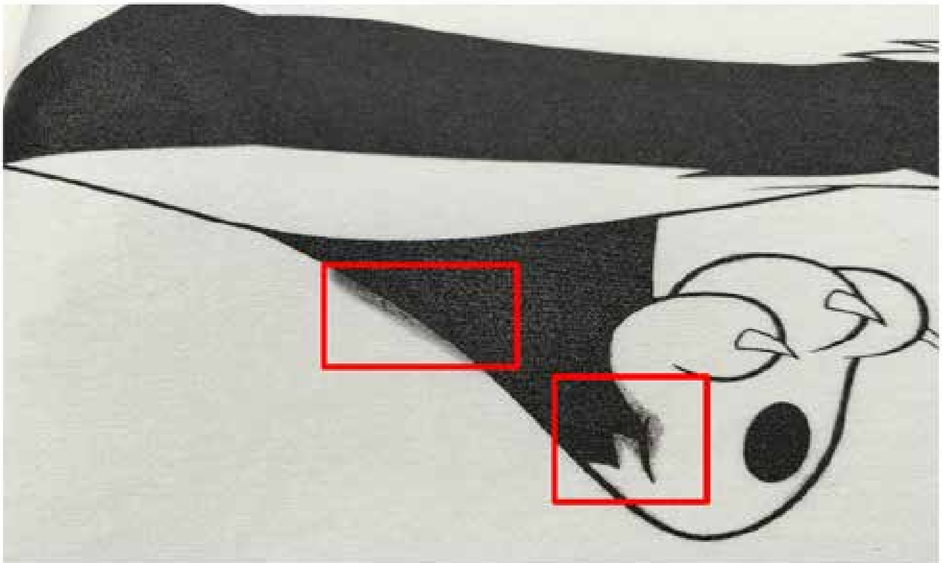


Ink Bleeding: In screen printing, an "ink bleeding" defect occurs when the ink spreads beyond the intended boundaries on the printing surface. This defect results in a blurred, unclear, or smeared appearance of the printed design.

The primary causes of ink bleeding include:

- Excessive use of ink
- Issues with the fabric surface
- Insufficient tension of the stencil

Figure 2
Example of an "Ink Bleeding Defect"



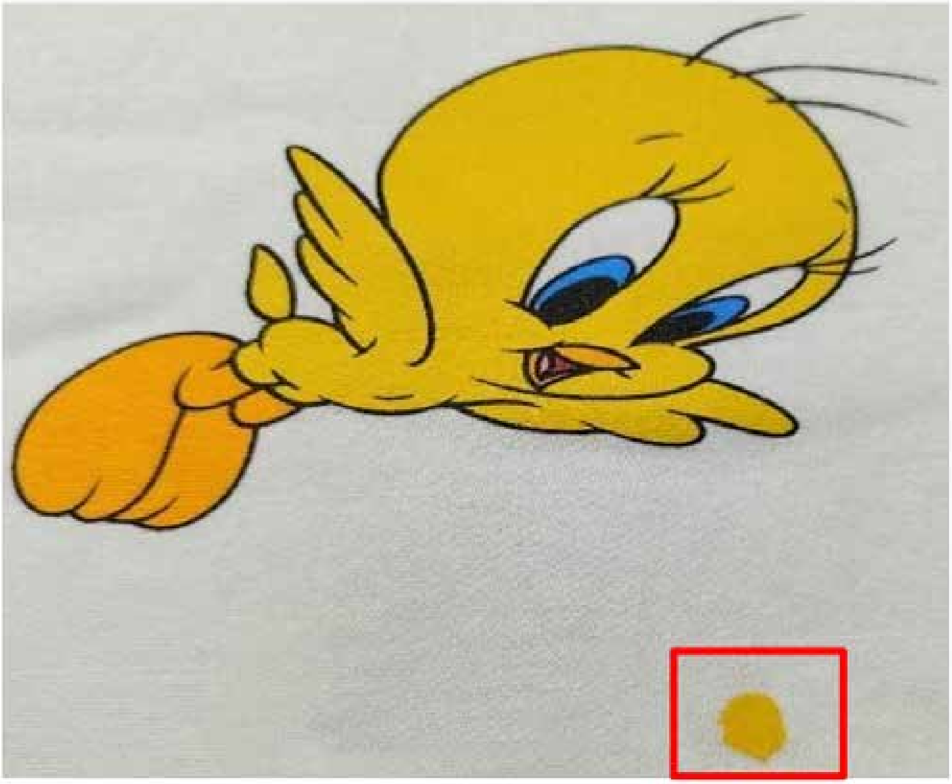
Ink Staining: In screen printing, an "ink staining" defect occurs when ink remains or spreads onto unintended areas of the printing surface, leaving unwanted marks. This defect prevents the print from appearing clean and sharp, negatively affecting print quality.

The primary causes of ink staining include:

- Inadequate cleaning of the stencil
- Excessive use of ink
- Incorrect ink viscosity

Figure 3

Example of an "Ink Staining Defect"



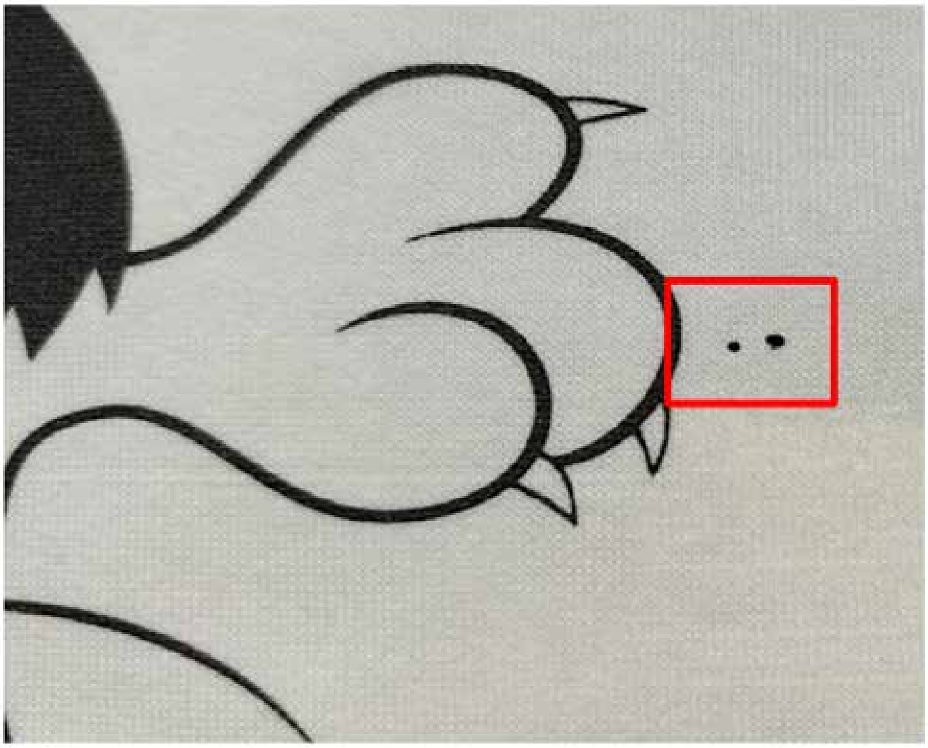
Stencil Leakage: In screen printing, a "stencil leakage" defect occurs when ink seeps outside the intended areas of the stencil during printing. This defect results in prints with blurred or distorted boundaries.

The primary causes of stencil leakage include:

- Damage to the stencil
- Incorrect application of the emulsion
- Improper sealing of stencil edge

Figure 4

Example of a "Stencil Leakage Defect"



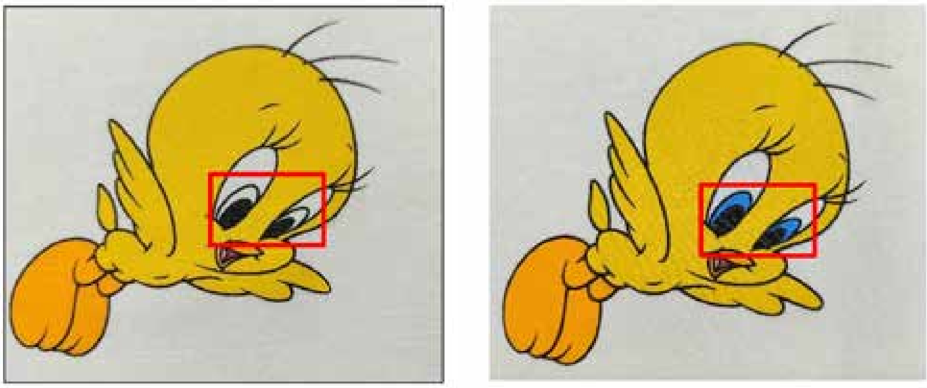
Stencil Clogging: In screen printing, a "stencil clogging" defect occurs when the mesh openings of the stencil become blocked by ink, dust, or other debris. This clogging prevents the ink from transferring properly onto the printing surface.

The primary causes of stencil clogging include:

- Inadequate cleaning
- Excessively thin or thick emulsion layers
- Dried ink residues

Figure 5

Example of a "Stencil Clogging Defect"

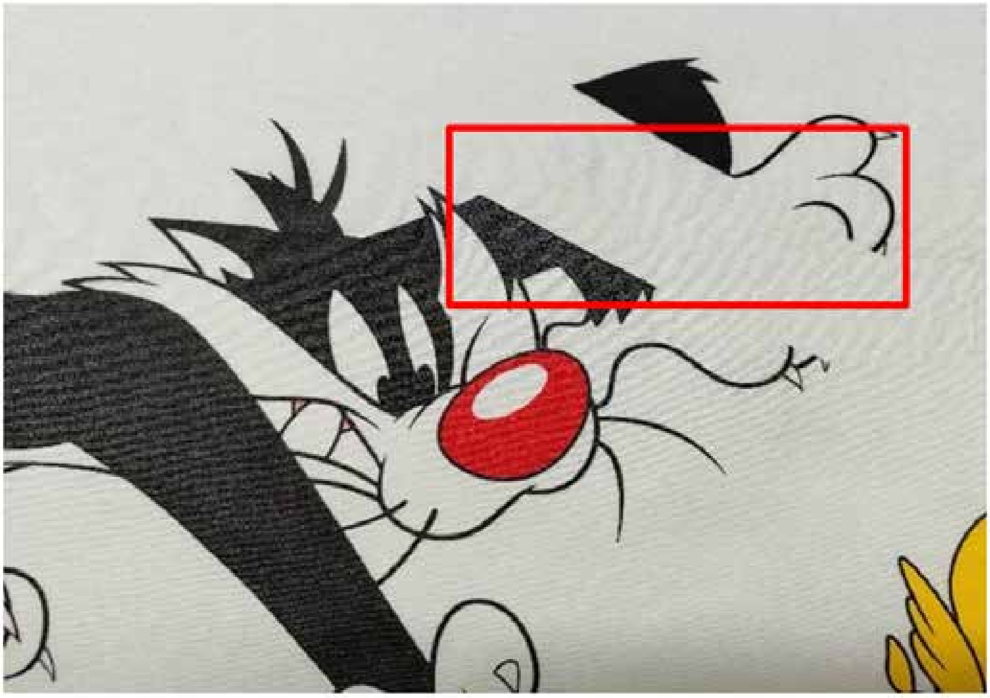


Fabric Folding: In screen printing, a "fabric folding" defect occurs when the fabric is not properly laid out before or during printing, causing folds or creases.

The primary causes of fabric folding include:

- Improper placement of the fabric
- Stretching of the fabric
- Misalignment in the printing machine

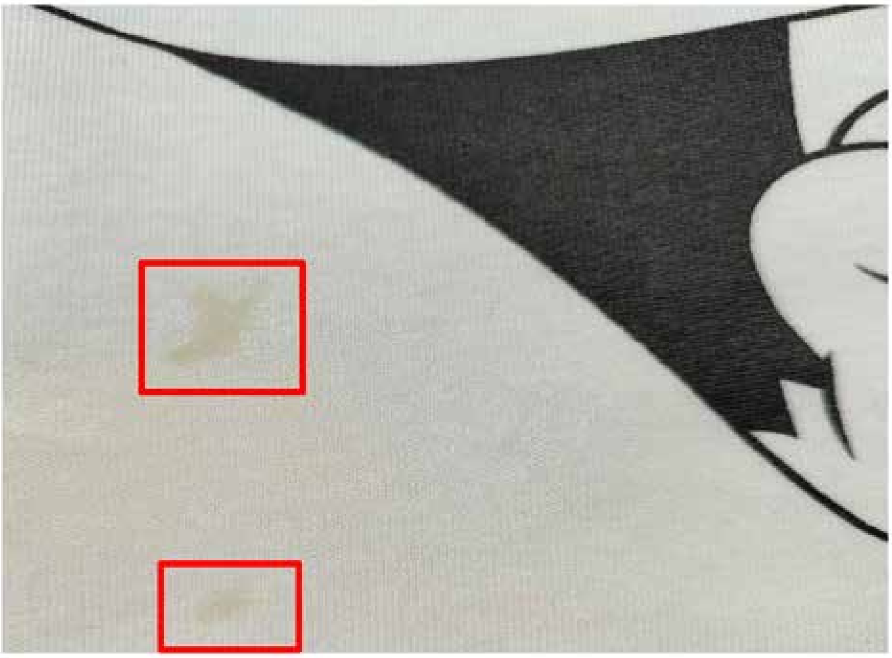
Figure 6
Example of a "Fabric Folding Defect"



Fabric Staining: Stains observed during the printing process are not caused by the printing itself; rather, they are pre-existing defects in the fabric. These stains are not directly related to the printing technique or the type of ink used, but originate from the fabric's manufacturing process.

Figure 7

Example of a "Fabric Staining Defect"



Embroidery defects

Embroidery Misalignment: In textiles, an "embroidery misalignment" defect occurs when the design produced by embroidery machines shifts or deviates from its intended original position. This defect prevents the embroidery from being executed accurately in the desired area.

The primary causes of embroidery misalignment include:

- Incorrect placement of the hoop
- Insufficient tension of the fabric

Figure 8

Example of an "Embroidery Misalignment Defect"

Embroidery Marking Defect: An "embroidery marking" defect occurs when unwanted marks, lines, or stains remain on the fabric during the embroidery process. These marks typically affect the outcome of the embroidery design or process and negatively impact its aesthetic quality. The primary cause of embroidery marking defects is the pre-marking of the fabric.

Figure 9

Example of an "Embroidery Marking Defect"

Thread Wrapping Defect: In embroidery machine operations, a "thread wrapping" defect occurs when the thread is not properly wrapped or when there are issues with thread tension during embroidery.

The primary causes of thread wrapping defects include:

- Incorrect thread tension
- Poor thread quality

Figure 10

Example of a "Thread Wrapping Defect"

Skipped Stitch: In embroidery machines, a "skipped stitch" defect occurs when threads are missing or entirely skipped in certain areas during the wrapping process. This defect results in unwanted gaps or deficiencies in embroidery design.

The primary causes of skipped stitches in wrapping include:

- Issues with machine settings
- Thread breakage

Figure 11
Example of a "Skipped Stitch Defect"

Embroidery Oil Stain: In embroidery, an "oil stain" defect is defined as a stain on the fabric caused by oil or oily substances during the embroidery process. These stains disrupt the aesthetic appearance of the embroidery and negatively affect the overall quality of the product.

The primary causes of embroidery oil stains include:

- Machine oils
- Improper or insufficient cleaning

Figure 12

Example of an "Oil Stain Defect"

Modern Quality Control Approaches

Traditional quality control methods have long been an indispensable part of the textile industry. Visual inspection relies on experienced operators examining product surfaces either manually or with the naked eye to detect defects. While this method offers advantages such as low technological requirements and flexibility, it also presents drawbacks, including errors arising from human factors (e.g., operator attention, fatigue, and lighting conditions), reduced efficiency, and inconsistencies. Visual inspection remains widely used, especially in low-budget operations; however, as quality expectations increase and production volumes grow, these methods need to be supplemented with modern quality control approaches.

The rise of automation and digitalization in the textile sector is transforming the quality control process. Technologies such as sensors, high-resolution cameras, automated testing devices, and IoT-based monitoring systems enable continuous data collection on the production line. This allows for both early defect detection and enhanced process traceability. For example, Metin & Bilgin (2024) investigated quality prediction using automatic machine learning models on imbalanced fabric quality datasets, demonstrating that this approach reduces operator dependency while making defects more predictable.

Image processing and AI-based applications constitute another key component that enhances the accuracy and speed of quality control. In a study by Ozek et al. (2025), deep learning models—particularly Convolutional Neural Networks (CNNs)—were employed for tasks such as identifying surface defects and automatically detecting anomalies during production. These technologies enable the detection of micro-defects that might be overlooked by the human eye, allowing defective products to be removed from the production line earlier and reducing material and cost wastage. Furthermore, the study by G. Nair and Trivedi (2024) demonstrated that adopting machine learning and artificial intelligence in quality control departments significantly improves production efficiency, accuracy, and cost-effectiveness.

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Damage Analysis of Carbon/ Glass Fiber Hybrid Composite Pipes

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Introduction

Composite materials have an important place in the industry in order to meet the innovations and increasing needs. In the studies carried out for the defense, space technologies, aircraft, automotive sector, which are important for the future vision of our country, materials with better properties have been sought. Designers have turned to composite materials in their search for materials with these properties.

A composite material is a new material formed by combining two or more materials with different chemical components and macro-level size ranges. Composite materials are superior to conventional materials due to their mechanical and chemical properties such as specific strength, specific gravity and corrosion.

The first use of composite materials in history dates back to the pre-bellum period, when the Egyptians used a mixture of mud and straw to create strong and durable buildings. Later, in 1200 A.D., the Mongols invented the bow and continued their work in the field of composites. While vegetable and animal resins were used until the early 1900s, synthetic materials such as vinyl, polystyrene, phenolic and polyester have shown better performance than those obtained from nature since the early 20th century. In the chronology of these studies, Owens Corning introduced the first glass fiber fiberglass in 1935 and stated that it was a light and strong material. Another one of the areas in question was the first composite commercial boat hull in 1946, adding a new one to its areas of use. Around 1975, as the composites industry developed, better resins and reinforcing materials were produced. DuPont developed an aramid fiber known as Kevlar, which became the product of choice for body armor due to its high tensile strength, high density and light weight. These developments paved the way for carbon fiber materials and replaced parts made of steel. Today, in addition to being used in sectors such as defense, space technologies and automotive, studies for the blades of wind turbines continue.

Made a comparison between two types of loading under biaxial loading of composite pipe specimens produced by filament winding method with different winding angles. They recorded the highest values according to the test values in the closed-end system from the loading conditions in the specimens wound with ±55 (Martins vd., 2013).

Mentioned that fiber reinforced composite materials are increasingly being used as an alternative to conventional materials due to their high specific strength, specific stiffness and special properties. At the same time, damping studies including macromechanical, micromechanical and viscoelastic (relaxation and creep) approaches were mentioned in the study and it was emphasized that they are suitable for high performance structural applications. They emphasized the impact damping advantages of polymer matrix composite materials (Chandra vd., 1999).

Investigated the damage behavior of FRP pipes manufactured by ±55° filament winding method under internal pressure. In the study, cracks were formed at different angles with respect to the axis of the pipe and in such a way that the wall thickness of the pipe was twice the crack depth. The bursting strength of the specimens was determined and the effect of the surface crack parameter was investigated. In the experimental study, it was concluded that the bursting pressure increased with increasing crack angle (Arikan, 2010).

Investigated the behavior of glass fiber/epoxy composite pipes under biaxial load. Tangential stress value of 290 MPa and axial stress value up to 165 MPa were obtained in composite pipes wound with a winding angle of 45°. As a result of the study, it was concluded that the stress ratio affects the linear elastic modulus (Ellyin vd., 1997).

Subjected glass fiber reinforced tubes produced by filament winding method to biaxial fatigue tests. The fatigue behavior of the material was investigated for tangential and axial loading conditions in the experiments. The fatigue event was performed according to ASTM D2992 standard and it was emphasized that larger (1-10 cm) matrix cracks were observed in areas with higher matrix density on the sample (Ellyin & Martens, 2001).

Investigated the damage behavior of glass fiber and epoxy composite pipes with 55° filament winding angle at internal pressure. In the study, it was stated that the cracks were perpendicular to the tensile direction in non-fiber areas and micro cracks occurred in fiber areas by separation of the fiber-matrix interface (Bai vd., 1997).

Fatigue and damage behaviors of glass reinforced plastic pipes made of E-Glass and epoxy materials under variable pressure were investigated. Samples with different winding angles were prepared in four layers and it was stated that both internal pressure values and fatigue life increased as winding angles increased (Gemi, 2004).

Investigated the fatigue behavior of glass reinforced composite pipes under internal pressure by damaging them with certain impact energy for winding angle ±55°. In the experiment performed in accordance with ASTM D 2992-06 standard, the damage energy of the glass reinforced composite pipe increased and the fatigue life decreased with the increase of the impact energy. It was emphasized that the damage was in the form of bursting in the pipes damaged with no impact and 5J impact energy, and in the form of leakage and pressure leakage in the samples damaged with 10J impact energy (Şahin, 2011).

E-glass/epoxy composite materials were subjected to heavy mass impact at low speed to investigate both in-plane dimensional and thickness effects. Impact tests were performed with a vertical drop weight tester using 150x100mm (±50mm) dimensions to investigate the dimensional effects and two nominal thicknesses of 1.4 and 2.8mm to investigate the thickness effect. As a result, it was concluded that the most important properties of composite materials subjected to impact loading are peak force and contact time, and the stiffness of the composite material is related to the width and thickness of the material (Aslan vd., 2002).

Investigated the effect of surface cracking by creating cracks at different angles in pipes made of glass reinforced material. They used low weights to create these cracks. Based on the ASTM D 1599-99 standard, they concluded that changing the angle of the surface crack has an effect on the burst pressure (Uyaner & Güvensoy, 2011).

Conducted fatigue tests on hybrid composite pipes and the first damage that occurs at low stress values is the separation of the fiber/matrix interface, which occurs in the direction of the fiber winding angle. These damages in the form of whitening grew in the fiber direction and formed matrix cracking in the following cycles (Gemi, 2016).

Reported that cylinders made of single-walled carbon nanotubes (SWCNT) are easier to bend and rotate and can be returned to their original shape after shape change, and that the tensile stiffness is higher than multi-walled carbon nanotubes (Yu vd., 2000).

Examined the effect of frequency lifetime on damage in their study and stated that the lifetime increases with increasing frequency, but this increases up to a certain point, that is, it has no effect on the lifetime after a certain frequency effect (Perreux & Joseph, 1997).

Investigated the damage behavior of GRP pipes obtained by filament winding method under internal pressure. They reported that the leakage damage in these pipes starts with the moisture formed on the pipe surface (Richard & Perreux, 2000).

Investigated the stress-strain deformation mechanism of carbon nanotubes (CNTs) and reported that CNTs have extraordinary flexibility properties and also have larger stresses without any sign of brittleness (Yakobson vd., 1996).

Reported that uniform distribution of carbon nanotubes in polymer matrices plays an important role in improving the properties of polymeric nanocomposites (PNC) (Soni vd., 2020).

Reported that the ideal winding angle for burst analysis, matrix cracking and fracture mechanisms is ±55° (Manoj Prabhakar vd., 2019).

Studied the dimensional analysis on impact damage and dynamic response of cylindrical structures made of glass/epoxy material and used specimens of different sizes and dimensions with ±55° winding angle. They reported that these manufacturing parameters significantly affect the physical properties of the specimen and the occurrence of damage (Tarfaoui vd., 2007).

Investigated the effect of bursting strength for the specimen of filament wound hybrid composite pipes under impact. Functionally graded hybrid composites, glass-glass/glass-carbon/ glass-carbon/ carbon-carbon-glass/ carbon-carbon were combined in different variations. Pipes were pre-stressed with internal pressures of 4, 16 and 32 bar. The effect of pre-stressing at different energy levels on the damage structures was studied. Pipes pre-stressed at 32 bar had the highest impact strength (Gemi, Kara, vd., 2016).

Reported that he studied Carbon/Glass/Glass (CGG), Glass/Carbon/Glass (GCG) and Glass/Glass/Carbon (GGC) as stacking array configurations. In this study, it was concluded that no leakage damage was observed in the pipes with GCG arrangement, while the pipes with CGG arrangement had higher impact resistance (Gemi, 2018).

Also examined the effects of winding angles of filament wound composite materials and produced and examined composites with 45°, 55°, 60°, 75° and 88° winding angles symmetrically and asymmetrically. As a result of the tests, they observed that the best properties were realized with 55° winding angle (Önder vd., 2009).

Reported that the blending of different types of reinforcing fibers such as glass, carbon, aramid and natural fibers with fillers such as calcium, carbonate, silica nanoparticles, clay, etc. improves structural properties in order to produce products with good properties compared to conventional materials (Santosh Savnur et al., 2020).

Studies have been conducted to investigate which mechanical properties CNTs, the most important reinforcing element used for reinforcement in the resin, the main phase of the composite material, impart to the resin. İnvestigated the improvement of mechanical and electrical properties of MWCNT-epoxy resin composites compared to composite structures made with pure epoxy matrix and reported that Young's Modulus and yield strength of polymer composites can be increased by 1 and 4%, respectively, with the addition of 1-4% MWCNTs to pure resin (Allaoui vd., 2002).

Reported that the interlaminar shear strength, fracture toughness and load transfer capability can be increased by adding nanoscale fillers such as carbon nanotubes through CNT/matrix (Üstün vd., 2016).

Reported that the hybrid composite strength depends on the properties of the fiber content of both fibers, the length of different fibers, fiber/matrix bonding and fiber sequence arrangement (Supian vd., 2018).

Preferred glass and carbon fiber composite materials for leaf spring production and conducted research on bending response. They reported that the bending response of leaf springs made of hybrid composite material was superior. Harmeet Singh and GurinderSingh Brar (2018) reported that the composite material leaf spring has high strength, low weight and low density in their study to compare conventional steel spring, metal matrix composite material spring and carbon epoxy based leaf spring (Rajesh & Bhaskar, 2014).

Reported in his study that for filament wound composite tubes , winding angle and number of layers are the parameters affecting impact toughness, and as the number of layers increases, the bending stiffness of composite tubesincreases during impact (Demirci, 2020).

Reported in their study that filament wound composite materials have replaced metal materials used in the production of pressure vessels and that composite tubes containing carbon fiber are one of the most effective solutions for high pressure vessels (Huang vd., 2020).

Reported in their study that as the tangential prestress level increases, the fatigue damage size increases and fiber breakage and bursting occurs after a certain loading (Gemi vd., 2017).

Reported that the resin system reinforced with multi-scale nanoparticles is suitable for industrial applications requiring high strength and thermal resistance (Taşyürek, 2021).

Reported in their study that crack growth rates and stress intensity change show a linear relationship and that the crack growth will increase as the stress intensity factor increases (Avci vd., 2007).

In summary, there are many studies in the literature examining the effects of fatigue, fracture toughness, machinability, impact strength and nano-additives on the matrix and composite structure of polymer matrix composite pipes. However, the differences between fabric winding technique and filament winding technique, prepreg material and normal fabric material, other production techniques and autoclave production techniques have not been sufficiently emphasized. In our study, material production was carried out using autoclave production technique using fabric winding technique, using both prepreg material and hybrid fiber CNT reinforced material combination. The aim of these materials is to determine the differences between normal fabric and prepreg material with balanced fiber/matrix combination and to compare autoclave production with other production techniques in different hybrid combinations at the same CNT reinforcement ratio.

Material

Properties of glass fiber prepreg material

Glass fiber prepreg material was supplied from SPM Composite company as SPM EGU 110 model fabric twill woven 110 g/m2 and stored in deep freezer by paying attention to cold chain transfer. Technical specifications of glass fiber prepreg materials are given in Table 1 and the supplied material is given in Figure 1.

Table 1

Glass Fıber Materıal Propertıes

Material	g/m^2	Woven	Weft(10cm)	Warp(10cm)	Weft	Warp	Width
Glass fiber	110	Twill	144	160	EC9 34	EC9 34	100

Figure 1

Glass Fiber Material

Carbon fiber material properties

In our study, Twill-430 gr/m2 carbon fiber prepreg material was supplied from SPM Composite company by paying attention to cold chain transfer. Technical specifications of carbon fiber materials are given in Table 2 and the material supplied is given in Figure

Table 2

Glass Fıber Materıal Propertıes

Material	g/m²	Woven	Weft(10cm)	Warp(10cm)	Weft	Warp	Width
Carbon fiber	430	Twill	29	25	12K	12K	100/127

Figure 2

Carbon Fiber Material

Nanotechnology and MWCNT

With the addition of carbon nanotubes, a balanced electrical conductivity and homogeneous nano-distribution in the material has resulted in an extra strength increase. MWCNT was supplied from Nanotek-Ankara and technical specifications are given in Table 3.

Table 3

CNT Technical Specifications

Purity	Outer diameter	İnner diameter	Length	Surface area
%95 CNT	10-20 nm	5-10 nm	10-30 µm	>200 m²/g

Autoclave Resin

Prepreg resin VTP DA100 model material was supplied from SPM Composite Company. Since we could not produce nano doped prepreg material, considering the decrease in the resin / matrix concentration of the prepreg material, nano doping was provided by using the same prepreg resin in order to add nano doping to the prepreg material. The supplied prepreg resin material is given in Figure 3

Figure 3

Resin

Cylindrical mold

The pipe used as a mold was obtained from seamless steel with an outer diameter of 72 mm and a length of 1300 mm by grinding the surface with a 0.1% taper. Our mold has a surface roughness value of N7 and the surface quality and taper are made to ensure easy mechanical removal of the composite material from the mold.

Figure 4

Cylindrical mold

Methods

One of the most frequently used methods in pipe manufacturing is filament winding.

However, this technique also has disadvantages such as the same fibers overlapping each other. It is also prone to production errors. The fabric winding method is preferred because the fibers are geometrically more regular in the form of fabric and production errors are at a minimum level. The point to be considered here is the degree of tension of the fabric during winding.

In our study, firstly, polyvinyl alcohol (PVA) mold release agent was applied on our hollow mold and covered with thin film nylon. For better penetration of the material into the mold, the mold was homogeneously heated to 50 °Cwith the help of a heater. Before the fabric winding process, a cover was produced for the mold so that it could be perfectly connected to the mold heads. Since one of the issues to be considered for the winding to be made in the turning process is the tension of the fabric, the prepreg material was wound on a pipe and the stretching process was performed. For the sequence parameters determined for the study in question, the process was completed by first applying resin to our pipe mold in the CGC sequence and wrapping four turns of carbon fiber, then two turns of glass fiber, and then four turns of carbon fiber again. The same process was performed for the GCG array.

Low Velocity Impact Test

Impact tests were carried out with a vertical weight testing machine. The testing machine is suitable for tests requiring low to medium impact energies. The mass of the impactor was 5.6 kg and the diameter of the impact nose was 12.7 mm. During the impact tests, an anti-kickback device was used to prevent multiple impacts on the target. The tests were performed at three different impact energy levels (5, 10 and 15 J).

The specimens with and without carbon nanotubes were impacted at least 3 times each at 5J-10J-15J energy values with a device with a cylindrical nose geometry. Since the selected material was both carbon fiber and carbon nanotube, no color separation was observed in the damage zone and it was not possible to observe it with penetrant liquid. The specimens impacted at 5 cm intervals were cut from the impact damage zone with a band saw and the damage zones were examined with a digital microscope. The results of the examination are given in the relevant section. The low-speed impact testing machine we used in our study is given in Figure 5.

Figure 5

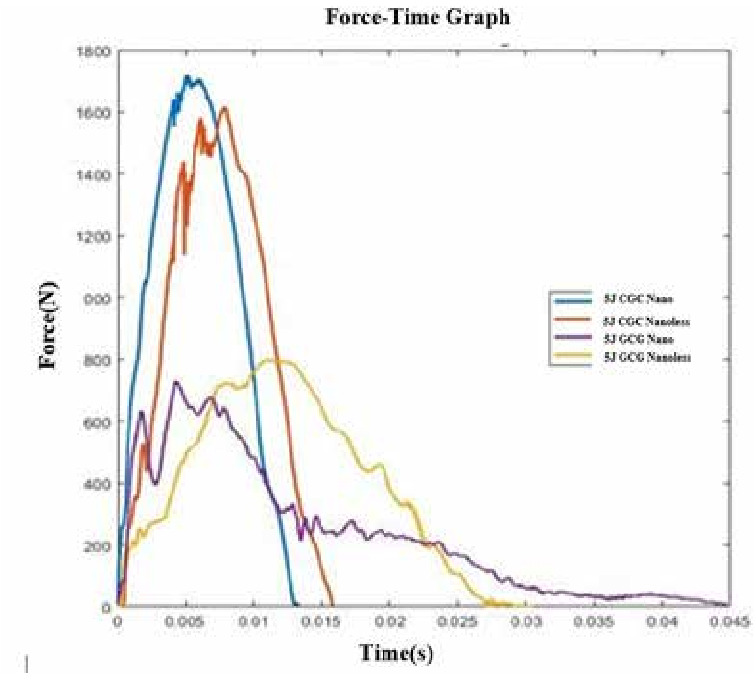
Low Speed Impact Device Test

Force- time graphs

Figure 6, Figure 7 and Figure 8 show the time-dependent variation of the contact force for different impact speeds. As can be seen, the contact force starts to increase at the first point of contact. This trend continues until Hertzian damage is encountered. Hertzian damage can be associated with matrix fracture damage encountered in the contact zone. However, the tubes may not lose their structural integrity and resist the applied deformation. Thus, an additional increase in contact strength is observed.

Figure 6

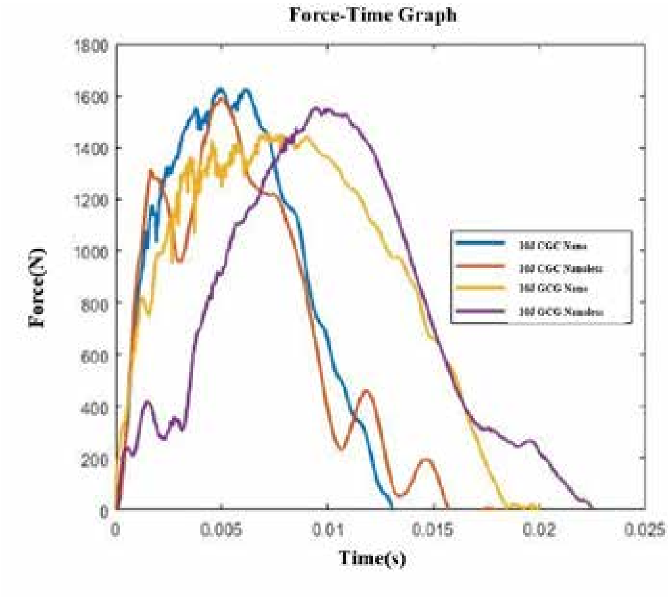
Test graphs with 5J



The difference between the material with and without nanos in the CGC array at 5J is 150-200 N. Earlier matrix cracking damage propagation was observed in the material without nanos. In the GCG array, the damage propagation at the same forces occurred in a longer period in the nanosized material, which leads to the conclusion that the nano reinforcement prevents the damage from spreading. Because the force contact time was realized in a longer period in the nanosized material. It is expected that the contact force is different between the CGC array and the GCG array. Because the CGC array is a stronger structure containing 8 times carbon.

Figure 7

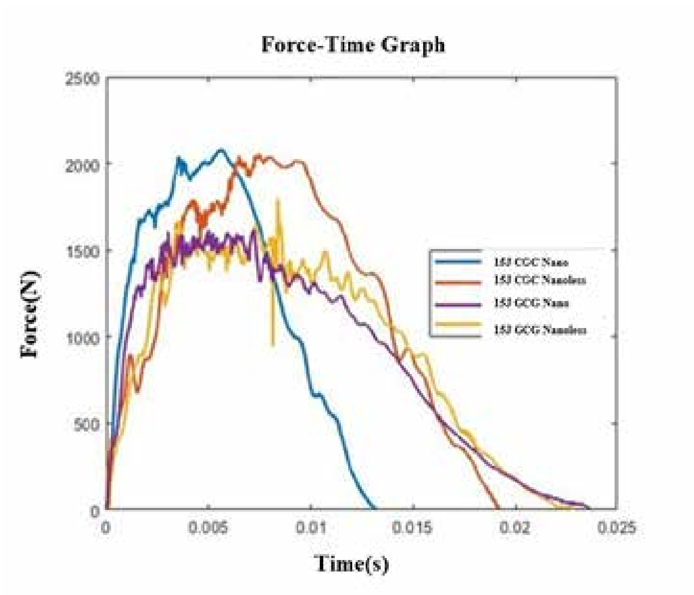
Test graphs with 10J



When the energy effect is increased, it is seen that the CGC array has a more stable structure in which the nanosilver materials have a larger force contact time compared to the materials with nanosilver and start to be damaged earlier.

Figure 8

Test graphs with 15J



In this graph, it can be said that the CGC array has a more resistant and brittle structure, while the GCG array has a more elastic structure. In contrast to the sudden matrix and fiber fractures in the CGC array, the GCG array shows deformation in a wider area spreading at a slower rate.

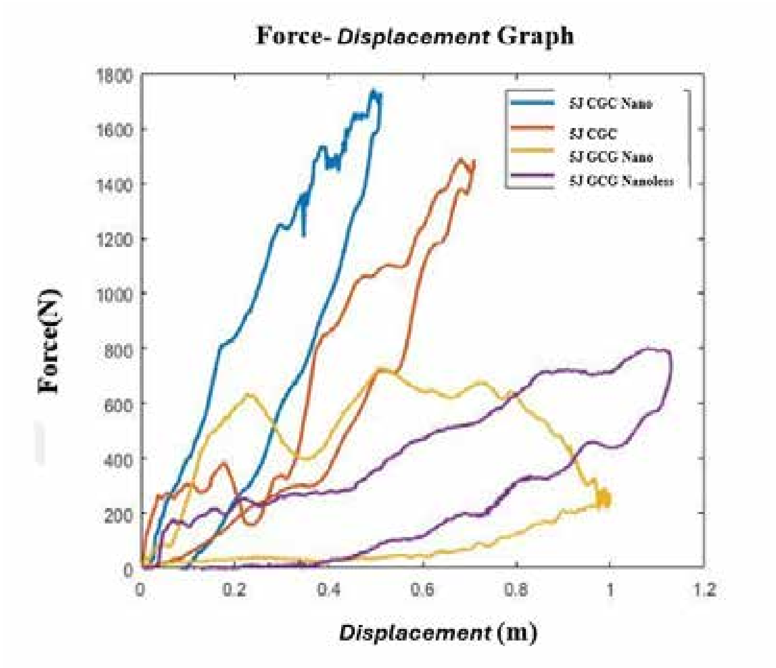
In general, when the force is increased, it can be concluded that the structures with nanotubes are damaged in shorter time periods at higher forces, while in the GCG array, this time period is more, so the damage area is wider and the fractures are more at smaller sizes. 1% nanotube additive reduces the damage of the materials and increases the force strength, but it is thought that the impact strength will increase at a more predictable level by increasing the nanotube additive up to 3% in accordance with the literature.

Force-displacement graphs

Figure 9, Figure 10 and Figure 11 show the change in contact force versus vertical displacement of the pipes. The slope of the contact force-displacement curve represents the bending strength. As the contact force starts to bend the pipe, a lower bending strength is observed. When the maximum contact force is reached, the displacement is also at its maximum value. Then the rebound phenomenon starts. It provides the remaining bending strength by pushing the impact tip back.

Figure 9

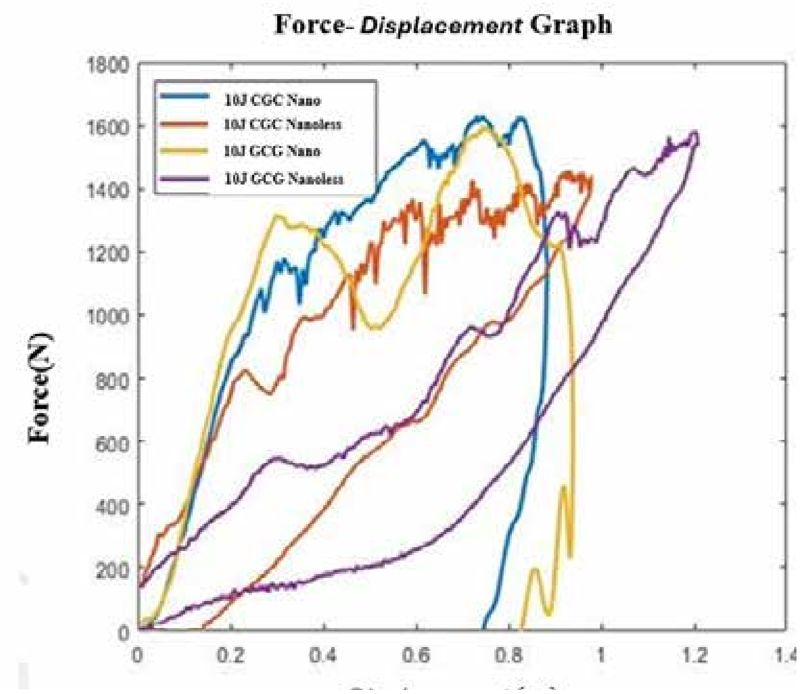
Test graphs with 5J



The material with CGC nanoparticles was destroyed at higher forces with a smaller displacement ratio and a stiffer rebound. In the non-nano material of the same array, lower force, earlier deformation, larger displacement and more moderate rebound occurred. In the GCG array, larger displacement and much lower rebound forces occurred due to a more flexible impact glass fiber. The non-nanosized version of this array has a larger displacement and therefore a larger deformation zone. This may be due to the more rigid structure of the carbon fiber layer under the glass fiber layer.

Figure 10

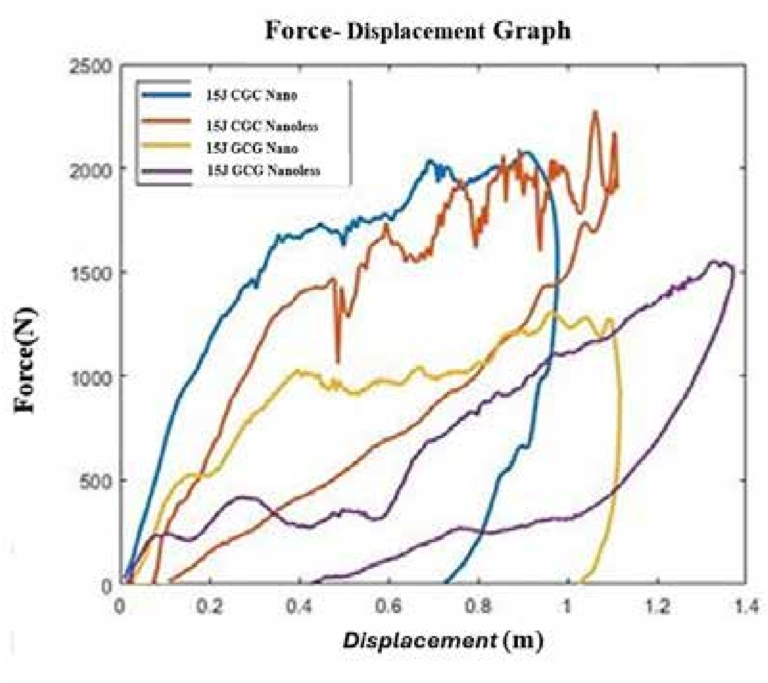
Test graphs with 10J



In the material with CGC nanoparticles, smaller-scale damage mechanisms occurred at high forces and the material reached a larger displacement period. Although the damage started later in the non-nanosized version of the same array, fiber fracture occurred, probably due to the effect of being non-nanosized, and after the material reached almost the forces of the nanosized version, the rebound effect was not fully visible due to the effect of fiber fracture and the material deformed. In the GCG array, the material started to be destroyed at lower forces. The material flexed significantly with the effect of glass fiber. In this array, the effect of the nanotube enabled the material to be damaged at higher forces with a smaller diameter.

Figure 11

Test graphs with 15J



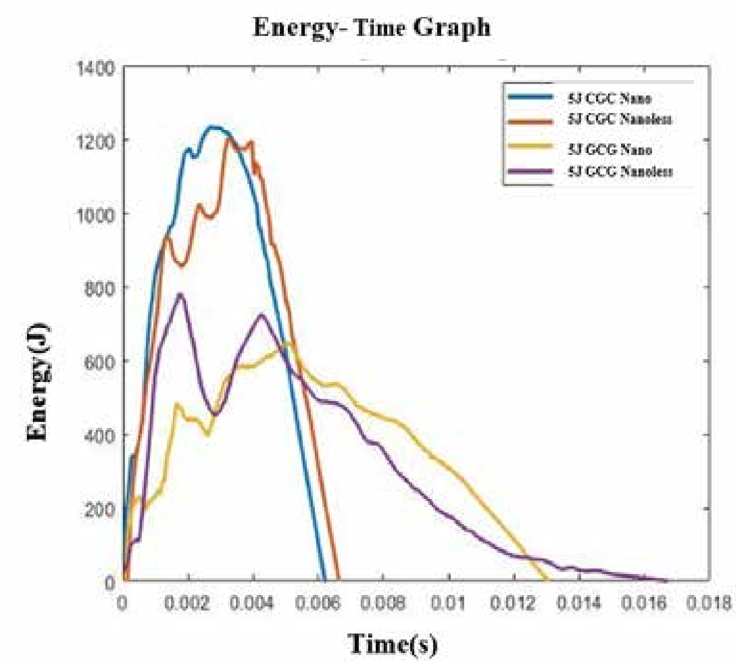
At this energy level, the material with nanos in the CGC array suffered small-scale and large-area deformation damages, while the material without nanos suffered stiffer and sudden damages, but reached higher strength. In the GCG array, relatively lower forces, larger deformation area and displacement rates were achieved.

Energy-time graphs

Figure 12, Figure 13 and Figure 14 show the change in energy with respect to time during contact for different impact velocities. As can be seen, the majority of the impact energy was spent on deformation and a small amount of energy was used for rebound. It can also be seen that the contact time becomes larger as the impact velocity increases in this specimen.

Figure 12

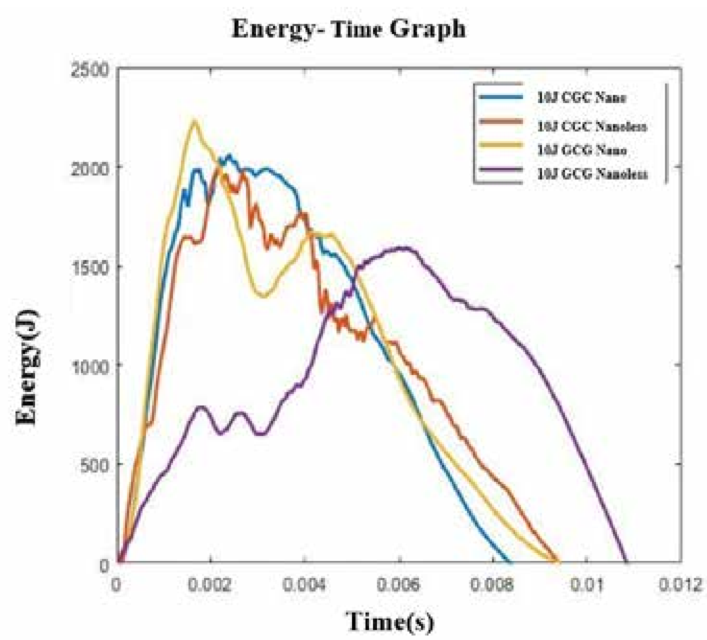
Test graphs with 5J



In the CGC array, most of the energy in the samples with and without nanos was discharged in a very short time. The amount of rebound energy was also spent in a very short time. Here, the nano difference is evident even if it is very small. In the GCG array, on the other hand, since it has a weaker flexible structure in terms of strength, the energy levels were discharged in longer periods of time and the material was destroyed more severely. This is because the glass fiber has a weak structure.

Figure 13

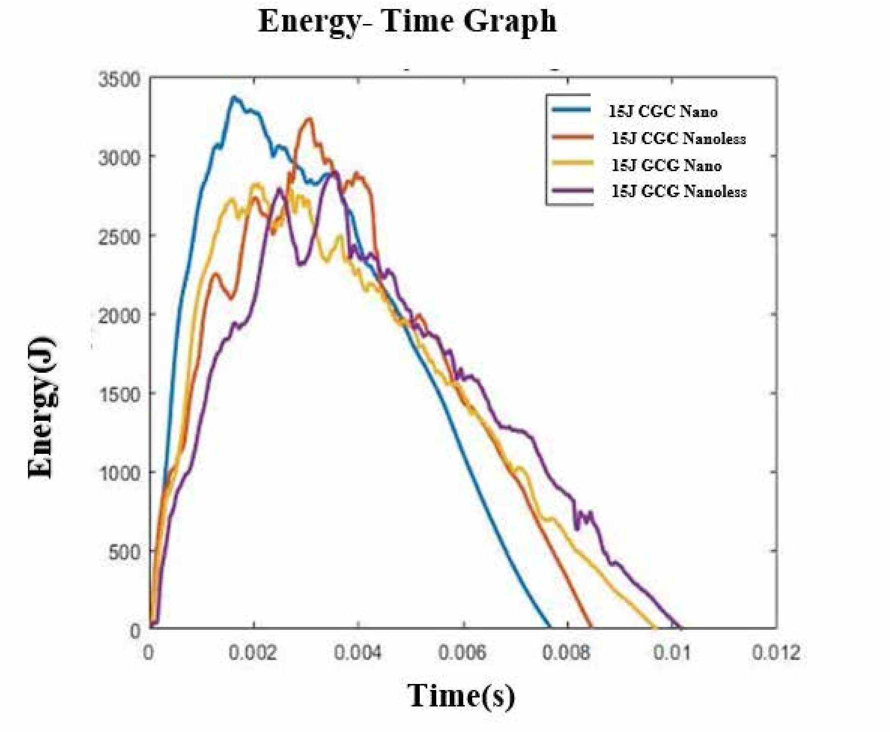
Test graphs with 10J



At this energy level, there is a relative parallelism in the CGC sequence. Energy is discharged in almost the same periods. It is seen that the nanomaterial deforms in a shorter time and consumes energy. In the GCG array, on the other hand, there is a sudden energy discharge due to high energy levels and high degree of fiber breakage in short periods. The reason for this should be further investigated. In the non-nano form of the same array, there is energy discharge with matrix breakage at lower energy levels and then energy increase with fiber strength. Due to its flexible structure, energy discharge occurred in a wider time period.

Figure 14

Test graphs with 15J



There is a correlation at this energy level for both arrays. All specimens were deformed with small matrix fractures, but again the materials with nanos were more severely damaged in shorter time periods. In the GCG array, especially the non-nano material was deformed with larger fiber fractures over larger periods of time.

Since the CGC array has a more stable and rigid structure in terms of strength, it absorbed more energy and spent this energy through matrix and fiber fractures. In the GCG array, there is a deformation with larger time periods and lower amplitude.

Effect of impact energy on the damage behavior of the specimen

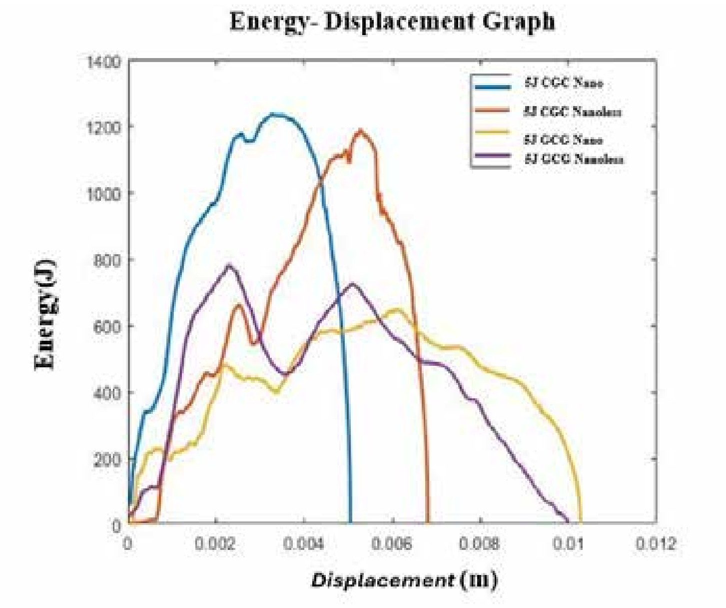
In the impact behavior of composite pipes, the ability of the impact tip to discharge the kinetic energy gained by the material starts from the moment the tip first touches the material. Since matrix cracking, fiber breakage and fabric winding technique are applied in composite materials, delamination damage is expected since each fabric layer will act as a laminate. However, the energy of the impact tip creates a deflection, i.e. collapse, at the material contact point. If the tip does not cause penetration in the material, the impact tip rebounds due to the impact resistance of the material, that is, the impact tip is pushed back by the material. In this case, the impact mechanism cannot discharge all of its energy to the material. All this mechanism creates a number of graphs and values that allow us to comment on both the impact resistance of the material and the damage caused by the impact tip on the material. These are force/time, force/displacement, energy/time and energy/displacement graphs and values.

Energy-displacement graphs

Figure 15, Figure 16 and Figure 17 show the energy-displacement plots and the deformation and rebound energy change/displacement change of GCG and CGC arrays are analyzed.

Figure 15

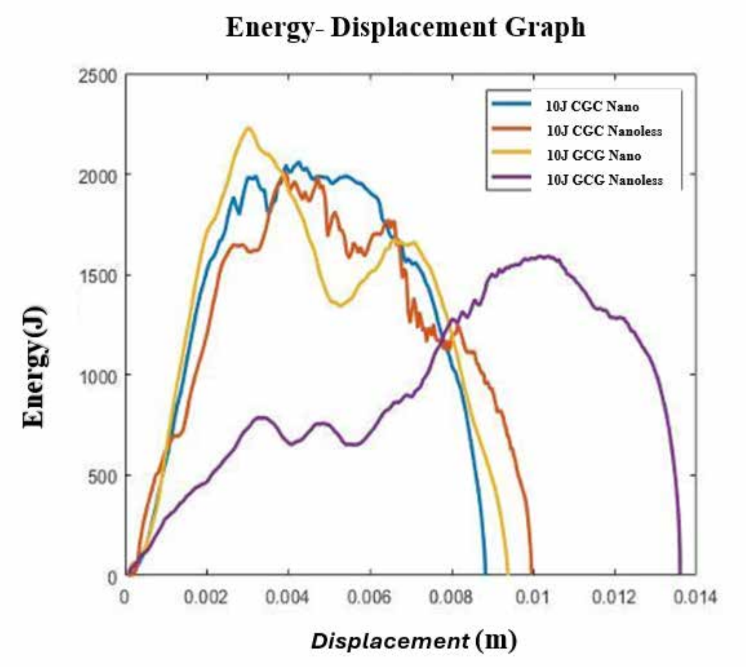
Test graphs with 5J



At this energy level, a higher amount of energy in the CGC array can be considered as a measure of the strength of the material as it creates lower displacement amounts. The fact that the nanoporous material in this array has a more stable structure shows the effect of nanotube doping. Despite the high level of energy expenditure, very small displacements were realized. The material without nanos has a larger displacement level with severe deformation damage. In the GCG array, since both samples have a more flexible structure, the structure with nanotubes consumed more stable energy and the structure without nanotubes was observed to deform with serious fiber fractures in a longer period.

Figure 16

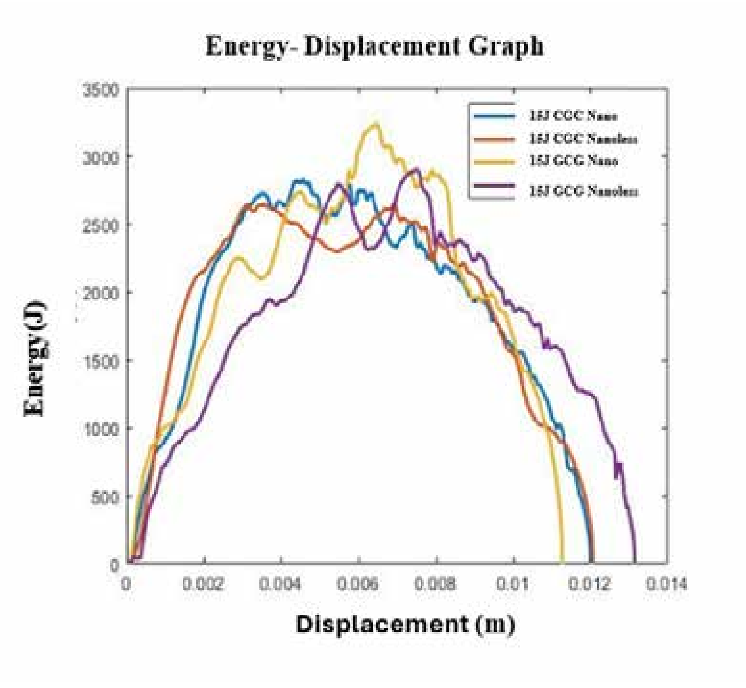
Test graphs with 10J



At this energy level, there is an equilibrium that does not resemble the nanotube difference of the CGC array. Sudden fractures, albeit very small, indicate a sample without nanotubes. In the GCG array, the material with nanotubes has a serious strength that we do not know the reason, but it absorbed energy at lower displacement rates due to very serious fiber fracture. The sample without nanotubes showed a more flexible structure and showed large displacement at low energy levels due to low stiffness.

Figure 17

Test graphs with 15J



At this energy level, in the CGC array, the nanomaterial absorbed energy stably at a large displacement ratio. The nanosized version of this array absorbed energy over a wide displacement range through matrix fractures at a relatively high level. In the GCG array, again, the material with nanosize absorbed energy stably and the nanosize version was more flexible and absorbed energy over a wide displacement range.

As the energy levels increase, it is seen in the graphs that the carbon nanotube difference in both sequences affects the material values very little. Nevertheless, nanomaterials exhibit more stable energy absorption and displacement ratios at all energy levels. Since the GCG array has a more flexible structure in terms of strength, it absorbed lower energy levels at larger displacement ratios. The carbon layers in the center of this array increased the energy absorption capability of the material.

Investigation of Damage Types

Nanolayered CGC array

Microscope examination images of the post-impact section of the nanolayer CGC array are given in Figure 18, Figure 19 and Figure 20.

As the energy levels increase in the nanomaterial, the number and orientation of fiber fractures in the damage zone increases. Delaminations are more balanced but tend to occur between the arrays. As the energy levels increase, the delamination lengths increase and the number of small delaminations increases in different regions.

Figure 18

Test graphs with 5J

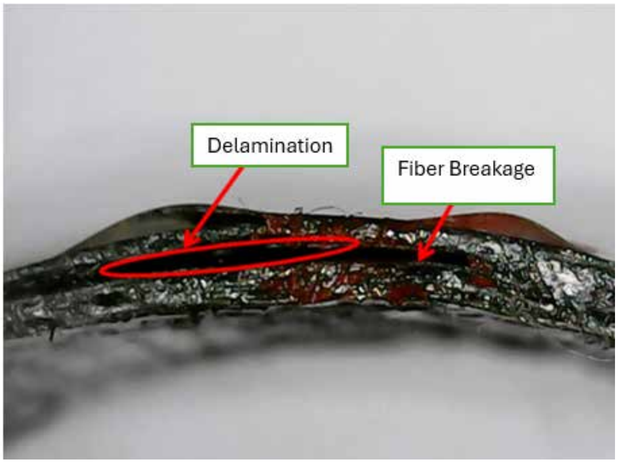


Figure 19
Test graphs with 10J

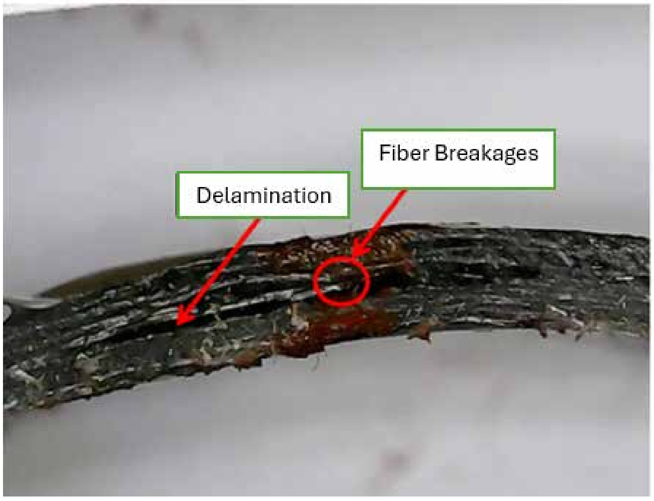
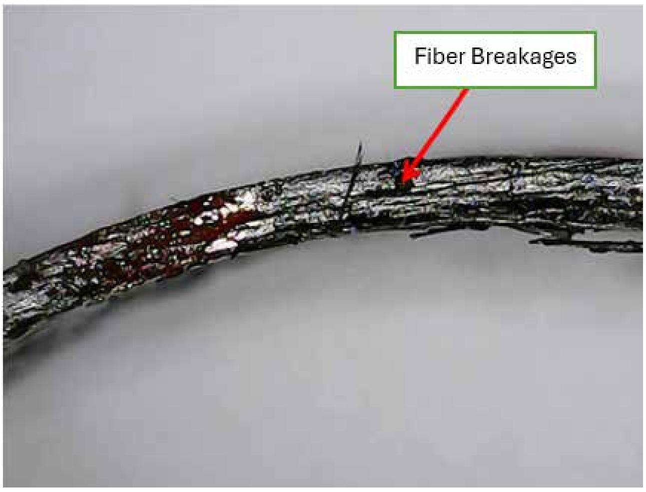


Figure 20
Test graphs with 15J



Nanoless CGC array

Microscope examination images of the post-impact section of the nanosized CGC array are given in Figure 21, Figure 22 and Figure 23.

Figure 21

Test graphs with 5J

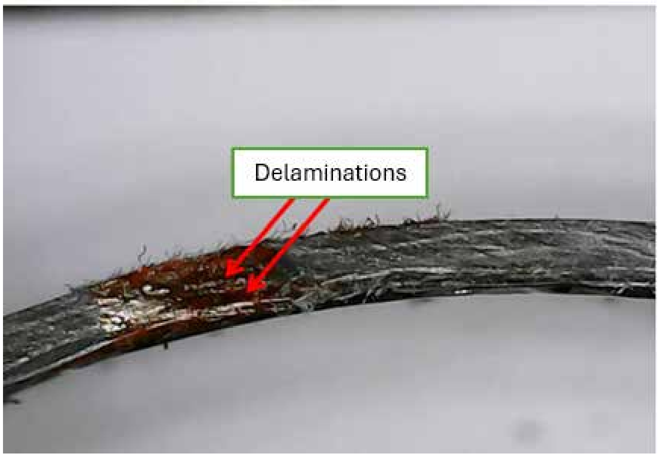


Figure 22

Test graphs with 10J

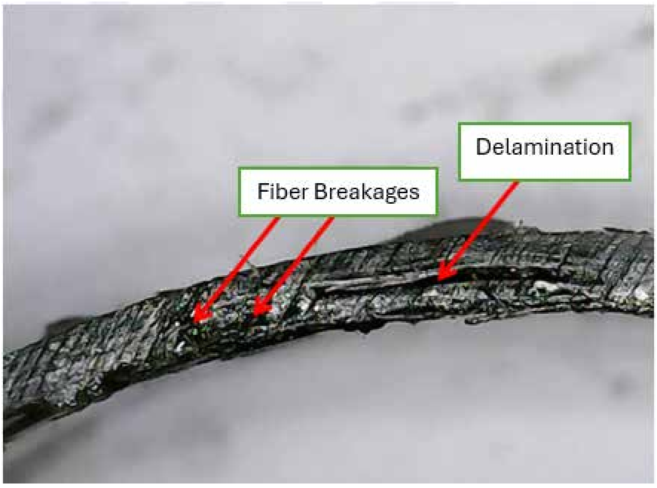
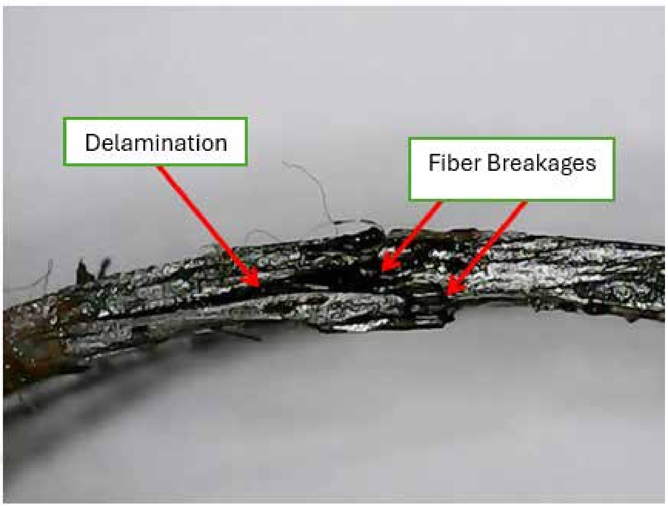


Figure 23

Test graphs with 15J



Fiber fracture and delaminations increased again as the energy level increased in the nanosilver material. At the energy level with 15J, delamination occurred.

When a comparison is made at the same energy levels of nanofibrous and non-nanofibrous materials, more balanced and stable fiber fractures and shorter delamination lengths are observed in the nanofibrous material. In the non-nano material, longer delaminations, stiffer fiber fractures and delamination are observed.

Nanolayered GCG array

Microscope examination images of the post-impact section of the nanolayer GCG array are given in Figure 24, Figure 25 and Figure 26.

Figure 24

Test graphs with 5J

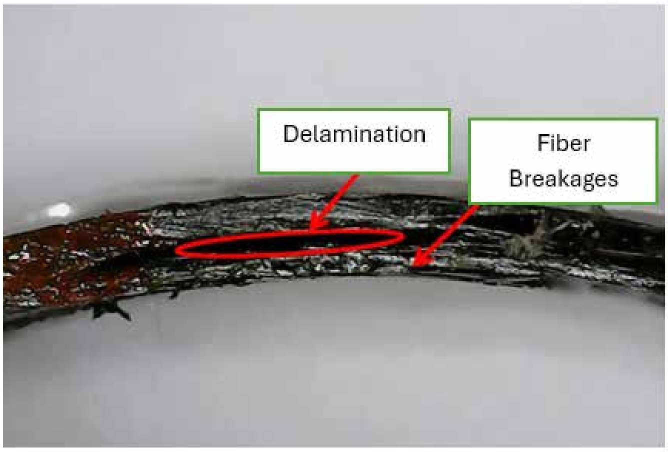


Figure 25

Test graphs with 10J

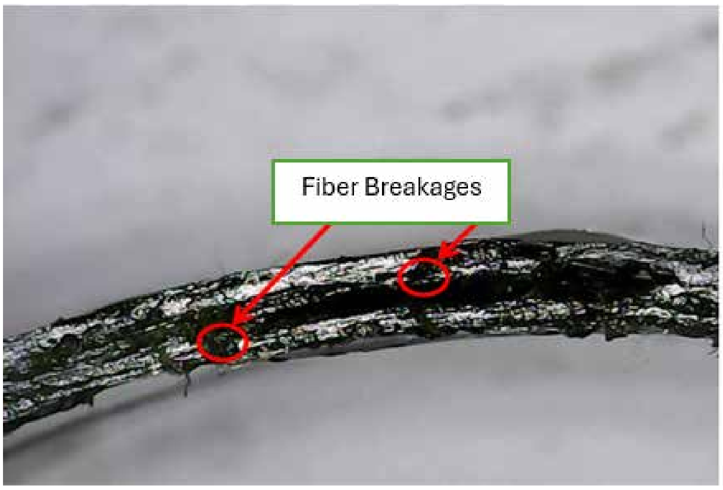
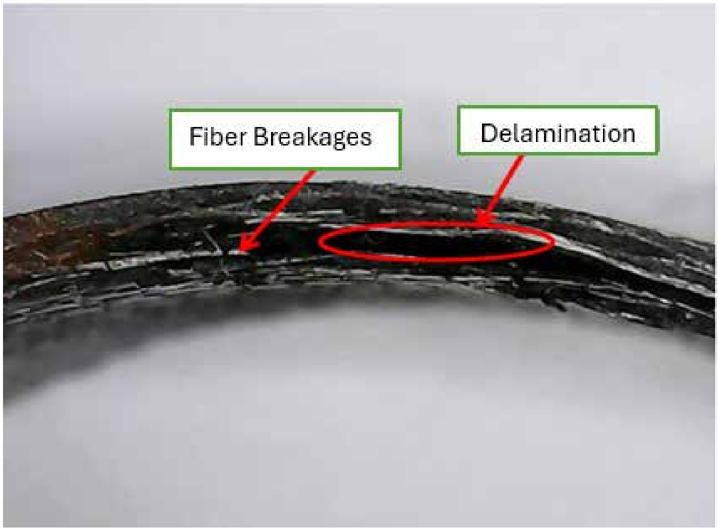


Figure 26

Test graphs with 15J



Since the GCG array contains 8 layers of glass fibers inside and outside and 2 layers of carbon fibers in the middle, it is a less strong structure compared to the CGC array. Therefore, the number of fiber fractures and delaminations continues to increase at increasing energy levels. Damage types are more stable in the material damage zone. Damages in the form of matrix cracks were observed on the impact tip contact surface.

Nanoless GCG array

Microscope examination images of the post-impact section of the nanosized GCG array are given in Figure 27, Figure 28 and Figure 29.

Figure 27

Test graphs with 5J

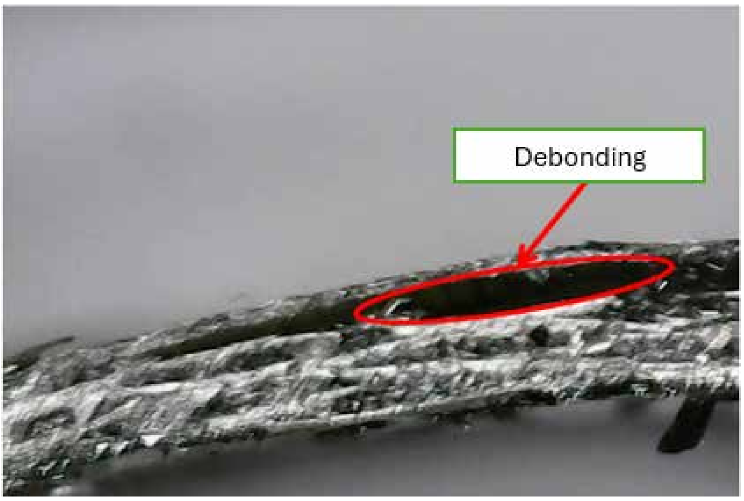


Figure 28

Test graphs with 10J

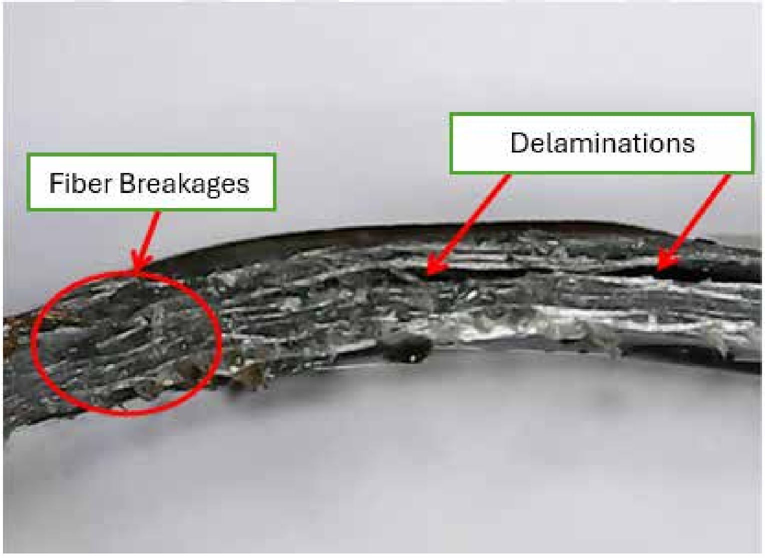
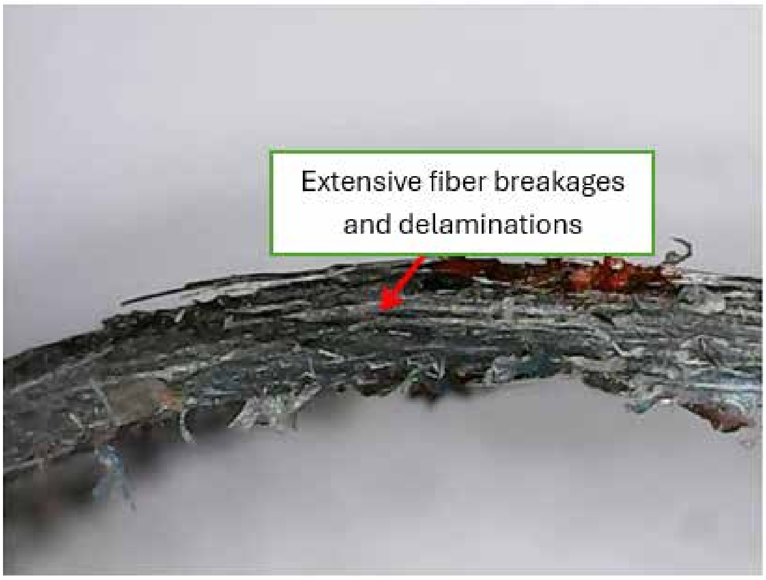


Figure 29

Test graphs with 15J



In this array, an increasing number of delaminations and fiber fractures were observed at increasing energy levels. At the 5J energy level, delamination between glass fiber and carbon fiber was observed. It is thought to be probably caused by a manufacturing defect.

When the damages were compared at equal energy levels with and without nanos in the GCG array, it was observed that the material with nanos was more stable, with shorter delaminations and fewer fiber fractures, while the material without nanos showed longer and more fiber fractures.

Results

Compared to the filament winding technique, the fabric winding method exhibits a structure similar to the layered composite production. This method has a function of reducing shear stresses compared to the filament winding technique. Since the preferred CGC array contains 8 layers of carbon, it is a more stable and rigid structure than the GCG array containing 8 layers of glass fiber. In this study, the effects of 1% carbon nanotube reinforcement on the impact strength of the hybrid structure at the layer level are as follows;

- CGC arrays have higher impact strengths than GCG arrays at the nanoporous and non-nanoporous level.
- Compared to GCG arrays, CGC arrays have higher energy absorption and rebound energy at lower time and displacement ranges with and without nanos than GCG arrays.
- In general, when the force is increased, it is concluded that the nanostructures are damaged in shorter time periods at higher forces in accordance with the literature, while in the GCG array, this time period is wider, so the damage area is wider and the fractures are more numerous in smaller sizes. 1% nanotube additive reduces the damage of the materials and increases the force strength, but it is thought that the impact strength will increase at a more predictable level by increasing the nanotube additive up to 3% in accordance with the literature.
- The material with CGC nanoparticles was destroyed at higher forces at a smaller displacement rate and rebounded harder. In the non-nano material of the same array, lower force, earlier deformation, larger displacement and more moderate rebound occurred. In the GCG array, larger displacement and much lower rebound forces occurred due to a more flexible impact glass fiber. The non-nanosized version of this array produced a larger displacement and therefore a larger deformation zone. This may be due to the more rigid structure of the carbon fiber layer under the glass fiber layer.
- In the material with CGC nanoparticles, smaller damage occurred at high forces and the material reached a larger displacement period. Although the damage started later in the non-nanosized version of the same array, fiber fracture occurred, probably due to the effect of being non-nanosized, and after the material reached almost the forces of the nanosized version, the rebound effect was not fully visible due to the effect of fiber fracture and the material deformed. In the GCG array, the material started to be destroyed at lower forces. The material flexed significantly due to the effect of glass fiber. In this array, the effect of the nanotube caused the material to suffer smaller damage at higher forces.

- Since the CGC array has a more stable and rigid structure in terms of strength, it absorbed more energy and spent this energy through matrix and fiber fractures. In the GCG array, on the other hand, there is a deformation with larger time periods and lower amplitude.
- As the energy levels increase, it is seen in the energy/displacement graphs that the carbon nanotube difference in both sequences affects the material values very little. Nevertheless, nanomaterials exhibit more stable energy absorption and displacement rates at all energy levels. Since the GCG array has a more flexible structure in terms of strength, it absorbed lower energy levels at larger displacement ratios. The carbon layers in the center of this array increased the energy absorption ability of the material.
- As a result, the homogeneous distribution of CNTs in the matrix, due to the large number of interfaces, increased the strength of the composite more in the CGC array than in the GCG array. In low reinforced specimens such as GCG array, 1% CNT reinforcement resulted in higher impact strength.
- The damage mechanism of unreinforced CNT pipes is fiber separation, first matrix fracture and then delamination and fiber breakage. MWCNT reinforcement led to crack tip opening instead of delamination, which reduces the strength of the interlayer.
- Optical monitoring of composite pipe cross-sections reveals visual and quantitative reduction of delaminated regions by the addition of nanoscale reinforcements to the epoxy matrix.
- Hybrid pipes with CGC stacking have higher impact resistance, while pipes with GCG stacking have larger damage area.
- It is concluded that the resistance to impact force increases when a carbon fiber layer is placed in the interlayer of the GCG pipe.
- The smallest displacement amount of the damage formation in the hybrid pipes during impact was obtained in the sample with CGC nanos, while the largest displacement amount was obtained in the sample without GCG nanos.
- The maximum contact force and contact time increase with increasing impact energy. The addition of CNT to the composite tube affected the displacement and the amount of energy absorption of the specimens during impact. For the same energy level, the maximum displacement value and minimum energy absorption were obtained from 1.0 wt% CNT doped tubes. CNT doping had a positive effect on the impact behavior of GRP tubes. This is because the addition

of CNT improved the interfacial bonding between the matrix and the reinforcing elements. Morphology characterization studies of the composites showed that CNTs were well dispersed in the polymer matrix at the nanoscale. Thus, it provides mechanical interlocking between the fiber and the matrix. Therefore, the laminar fracture strength was increased and low-speed impact resistance was improved.

When the microscope images are examined;

- As the energy levels increase in the CGC nanofiber material, the number of fiber fractures and their orientations increase in the damage zone. Delaminations are more balanced but tend to occur between layers. As the energy levels increase, delamination lengths and numbers increase.
- In the CGC nanosilver material, fiber fracture and delaminations increased again as the energy level increased. At the energy level with 15J, delamination occurred.
- When a comparison is made at the same energy levels of CGC nanoporous and non-nanoporous materials, more balanced and stable fiber fractures and shorter delamination lengths are observed in the nanoporous material. In the nanosilver material, longer delaminations, stiffer fiber fractures and delamination are observed.
- Since the GCG array contains 8 layers of glass fibers inside and outside and 2 layers of carbon fibers in the middle, it is a less strong structure than the CGC array. Therefore, the number of fiber fractures and delaminations continues to increase at increasing energy levels in GCG nanomaterial. Damage types are more stable in the material damage zone. Damages in the form of matrix cracks were observed on the impact tip contact surface.
- In the GCG material without nanos, an increasing number of delaminations and fiber fractures were observed at increasing energy levels. At 5J energy level, delamination between glass fiber and carbon fiber was observed. It is thought to be probably caused by a manufacturing defect.
- When the damages were compared at equal energy levels in the GCG nanofiber and non-nanofiber materials, it was observed that the nanofiber material was more stable, with shorter delaminations and fewer fiber fractures, while the non-nanofiber material had longer and more fiber fractures.
- Further studies are planned to compare the production of composite material with circular cross-section by fabric winding technique with the production of carbon fiber material by filament winding technique.

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Introduction

Background of the Study

The researcher had the opportunity to observe various academicians in the field of industrial design conducting project courses during their undergraduate, master's, and doctoral education at Istanbul Yeditepe University, Mimar Sinan Fine Arts University, and Konya Selçuk University. These observations extended through their tenure as a research assistant and faculty member at the same institutions. While serving as an assistant professor and supervising project courses, the researcher further enriched their previous experiences. Over time, it became evident that project courses were often conducted in a trial-and-error manner. The researcher observed a persistent complexity in these courses, characterized by interdependent projects, a multitude of variables influencing the process, and continuous effects on the project outcomes. Although measures such as segmenting the project development process and preparing structured project briefs to guide students showed partial benefits, these steps were insufficient to reduce the prevailing chaos effectively. The primary aim of this research is to leverage observations and experiences to mitigate the identified complexity in project courses, thereby facilitating a more structured and efficient execution of projects and contributing to improved educational outcomes.

Problem Definition

As a multidisciplinary field, industrial design necessitates diverse intellectual and cognitive skills for both students and instructors in project courses. The coexistence of explicit and implicit aspects within these courses contributes to their inherent complexity. Furthermore, the diverse characteristics of students, instructors, and institutions involved in project courses exacerbate this complexity.

To address this, it is essential to understand the impact of instructors and industrial design curricula on student outcomes, elucidate the processes and stages of project development, enhance students' intellectual capacity and behavioral approaches to the course, and equip them with the skills required by the industrial design discipline. A more structured and controlled approach is needed to manage the chaos observed in project courses effectively.

Research Questions

To guide the study and define its scope, the following research questions have been formulated:

1. Who are the visible actors actively involved in project courses?

2. What are the visible non-human factors influencing project courses?

3. What are the potentially impactful but invisible factors in project courses?

4. How do visible and invisible, human and non-human actors form a network of relationships within project courses conceptualized as a social network?

5. Which actors occupy central positions in the network, and how do they influence design outcomes in project courses?

Industrial Design: A Discipline Rooted in Serial Production

Industrial design is intrinsically connected to serially produced products. Unlike engineering design approaches, the criteria for design in serial production place the designer in an environment dominated not only by problem-solving but also by creativity. This positions the industrial designer to address operational requirements that involve multiple disciplines. Industrial designers reinterpret innovations brought by science and technology to benefit humanity. They often find themselves collaborating with interdisciplinary teams, including those from business and engineering domains.

The Industrial Designers Society of America (IDSA) defines industrial design as follows:

"Industrial design is a professional service of creating and developing concepts and specifications that optimize the function, value, and appearance of products and systems for the mutual benefit of both user and manufacturer" (IDSA).

Industrial design can also be defined as a profession and field of expertise that involves designing the attributes, concepts, forms, and functions of products and systems intended for mass production. This process considers criteria such as product-user interaction, aesthetics, identity, ergonomics, usability, technical aspects, and socio-economic factors (Warell, 1999).Based on the definitions above, industrial designers focus primarily on the following factors:

1. Product-User Interaction:Designers aim to optimize the usability and functionality of products while addressing their intended purpose. This involves examining similar products to identify and resolve design problems.

2. Aesthetics:Aesthetics not only entails making products visually appealing but also ensuring a semantically accurate visual language aligned with the relationship between form and function. Additionally, aesthetics contributes to how the product conveys its purpose and usability while considering the emotions it evokes in users.

3. Cost:Designers are responsible for ensuring the economic feasibility of their products for both consumers and manufacturers. Thus, they must design products that can be produced with minimal materials and time.

4. Product Identity:Identity plays a pivotal role in positioning a product strategically in the market and establishing a connection with a brand's other products.

5. Sustainability:Designers are tasked with creating products that are safe for both humans and the environment over the long term. This necessitates integrating concepts like ergonomics, sustainability, and green design into the design process.

Despite its broad scope, industrial design is only one part of the overall product development process. Other components include planning and preparation for production. The field of product design encompasses both industrial design and engineering design (Warell, 1999). Engineering emphasizes the analytical aspects of design, focusing on technical specifications. These often include areas such as mechanics, structural integrity, aerodynamics, hydraulics, electronics, software, systems, total quality management, economics, and human factors (Warell, 1999).

What sets industrial designers apart from engineers, business professionals, and other disciplines is their ability to synthesize creative and rational methods simultaneously to achieve innovative ideas. While doing so, designers often encounter unforeseen constraints and variables during the process.

As highlighted by Rittel and Weber in their 1973 work on "Wicked Problems," design problems, unlike those in engineering and natural sciences, lack singular, definitive, and ultimate solutions. This complexity also complicates the educational context of project courses, as the answers to design challenges form a rich but ambiguous pool of possibilities. Consequently, design studies do not aim for definitive conclusions but rather strive to identify and refine the most feasible solutions by borrowing from alternative approaches. Designers navigate conflicting values and constraints, ultimately achieving superior solutions through compromise and maneuvering. Yet, even at the end of the design processes, there are no absolute truths (Shön, 1987).

Proposed solutions serve as tools to better comprehend and address the resistance inherent in ill-defined design problems (Cross, 1989). Modern industrial designers must adapt to the complex expectations of both producers and consumers while keeping pace with current technologies and trends. Examples include advancements in computer-aided design and manufacturing, the proliferation of 3D printing, and the integration of artificial intelligence in the design domain.

The Origins of Studio Culture

The emergence of the studio-based education model predates the establishment of industrial design as a profession and discipline, making it worthwhile to explore the historical roots of the studio system. Unlike the traditional amphitheater-style education model, where knowledge is unilaterally transmitted from teacher to many students, early examples resembling studio-based education, characterized by mutual exchange of ideas and discussions, can be traced back to Plato's Academy, founded in 386 BCE. At his academy, Plato spent much of his life debating, developing, and writing his ideas (Pevsner, 1940). These discussions fostered a free and intuitive structure that allowed students to develop both creatively and intellectually (Readers, 1984).

A resurgence of Platonism occurred in late 15th-century Italy, where schools based on humanism—offering free, informal, and open discussions—emerged as alternatives to the universities of the time. Leonardo da Vinci and Michelangelo trained their apprentices in a studio-style education model in the fields of art and sculpture. Their approaches distinguished art from craft and emphasized that painting was not merely a manual skill but also a spiritual form of expression (Pevsner, 1940).

Traces of modern studio culture can be observed in both Plato's informal humanist discourse and the Renaissance's master-apprentice relationship, where creative imagination was emphasized more than logic and analytical thinking (Green, 2005).

The lineage of studio education can be traced through institutions such as the Académie Royale d'Armatür, École des Beaux-Arts, and École Spéciale d'Architecture, which provided training in painting, sculpture, and architecture. These schools were established as part of a deliberate strategy to sustain a consistent flow of skilled designers proficient in drawing and technical representation, laying the foundation of French design philosophy (Heskett, 1997). At École des Beaux-Arts, critiques, discussions, and idea exchanges were integral to studio sessions, while theoretical courses on subjects like mathematics, geometry, mechanics, perspective, and drainage were taught in amphitheaters. Within this framework, the "architectural studio" emerged as a distinctive format of architectural education, blending theoretical curricula with studio sessions.

These studios were modeled after traditional workshops, supported by patrons, and often involved contractual agreements (Bingham, 1993). Notable figures of modern architecture such as Frank Lloyd Wright and Le Corbusier were trained within this system (Proudfoot, 1989).

Industrial Design Studios and Studio Culture

Design studios where project courses are conducted are typically large classrooms equipped with drawing tables and seating to allow students to work independently on their projects. Proper and natural lighting in these spaces is essential for productive work. Additionally, walls in these studio-based classrooms are often designed to display and showcase student work. Unlike traditional amphitheaters, design studios are shaped for presentations and discussions, where the phases and requirements of design projects are explained. The teaching, design, and learning processes in project courses are managed by a design instructor and supporting assistants. These project courses are rooted in an apprenticeship model where values, skills, and knowledge are transferred from instructor to student (Kapkın, 2010). While this relationship has evolved, it remains relevant in current courses, albeit with some differences. In traditional craftsmanship, apprentices could directly observe their mentors practicing their craft. However, in many cases, students today do not have access to such direct observation. Design studios often include workshop equipment, model materials, and computers that enhance students' experiences with form and function. These facilities support "learning by doing," helping students refine and internalize abstract aspects such as a sense of form. Workshops where students can create models of their designs using materials like wood, cardboard, and foam are critical for learning and teaching.

Models represent objects, and modeling signifies the process. Ultimately, creating models is a process that provides answers (Giard, 1999). In contemporary industrial design curricula, project courses are central because they teach students how to visualize and present a product, a problem, or a solution as a design. Emphasis in the design studio is placed on creativity, drawing, problem-solving, and communication. Project courses provide an environment where values, skills, and knowledge are conveyed in a spirit of open inquiry, allowing students to learn to "think like designers" (Maitland, 1991).

Thinking like a designer involves perceiving and addressing essential, often overlooked aspects of design. It encompasses discussion, assumption, imagination, and defining boundaries. The supported thinking style in design studios is often described as random, intuitive, holistic, synthetic, and subjective. This thinking style ties into concepts of talent, creativity, and art, all associated with imagination and synthesis.

The teaching and learning approaches in industrial design studios differ from those in natural sciences and engineering disciplines, which are based on principles, rules, methods, and formulas applicable to rational problems. This difference stems from the nature of design problems encountered in the real world, which are not rational like those in the sciences. Studies describe these design problems as ill-defined, resistant to straightforward solutions, and difficult to analyze (Rittel, 1973).

The industrial design studio project may encompass the design of visual, auditory, and tactile interfaces that influence the overall quality of product design, functionality, and appeal. These interfaces serve as formal extensions that establish a connection between the user and the product, fostering an emotional bond. Additionally, industrial designers work with materials and structural elements that must be suitable for manufacturability, assembly, use, and environmentally safe disposal at the end of their lifecycle. As a result, addressing ill-defined industrial design problems requires simultaneous consideration of numerous factors and constraints (Talbot, 1999).

Such design problems are typically resistant to resolution and are often described as ill-defined or poorly articulated. Rowe provides a summary of the characteristics of these "wicked problems," first defined by Rittel, which can be interpreted as resistant to solution. First, Rowe highlights that these problems lack specific formulas or clear pathways for resolution, requiring iterative refinement through continuous questioning. Second, these problems lack a clear foundation and terminology necessary for initiating problem-solving actions, and there are no definitive indications of reaching a final solution. In other words, the problem-solving process cannot be abruptly halted after arriving at relatively good solutions; there is always room for improvement and the possibility of a better solution. Third, the formulations of these problems lead to alternative solutions, allowing for diverse interpretations. These formulations and solutions can span a wide spectrum, offering various paths to address the issue. Finally, none of the proposed solutions can be deemed right or wrong. Proposing solutions to design problems is merely a tool for understanding and addressing resistant and ill-defined challenges (Cross, 1984).

Therefore, recognizing and addressing these resistant and ambiguous design problems is essential. Teaching students how to identify and tackle such challenges forms the backbone of education in the design studio. Recognizing and addressing such problems, as well as teaching students how to find and manage them, form the backbone of education in design studios. Critiques of student work by instructors lie at the heart of studio education. Critiques aim to identify logical or visual errors in a student's work and guide its evolution into a more accurate and aesthetically pleasing outcome. Project courses typically begin with the identification of a project topic. Students then explore various solutions and sub-solutions throughout the design process, which includes searching for and synthesizing relevant information. The synthesis of information helps clarify design problems and facilitate the development of alternative solutions.The design studio's natural environment fosters the emergence of diverse ideas and perspectives through discussion, critique, defense, and exchange of ideas. Students in the studio experience its natural setting, characteristics, and requirements. For example, adding aesthetic or semantic attributes, assigning identity, and integrating regional, cultural, or emotional characteristics into a product is integral to studio education.

The inherent structure of industrial design studios enables the identification of design problems before they arise, ensuring healthier project progression and better outcomes through iterative processes. Students' imagination and creativity are crucial for both functional solutions and achieving formal richness. These qualities are often nurtured by students' prior experiences and intellectual accumulation.To meet the requirements of design projects, students often rely on prior coursework, typically derived from other disciplines.

Courses such as technical drawing, computer-aided design, ergonomics, material knowledge, manufacturing methods, and advanced drawing techniques support project courses when tailored to the character of industrial design and integrated into studio culture. A curriculum focused on anticipated design problems encourages professional practices more effectively than academic courses disconnected from practical applications.

The foundation of studio-based learning lies in students discovering clues and puzzles related to design problems they wish to solve. The need for organized knowledge clusters borrowed from other disciplines arises only when such knowledge is required to solve design problems (Boud, 1985). Problem-based studio learning relies on students' ability to understand, experience, and conceptualize the world around them. This approach reflects the expertise of industrial design, encompassing its methods, experiences, and concepts (Ramsden, 1992).Project-based learning in design courses requires students to work more independently than in other disciplines.

While experienced design instructors and assistants provide guidance, responsibility for maintaining design processes, identifying problems, developing solutions, making decisions, accessing resources and information, and adapting these to project designs ultimately falls on the students. This alignment with the "learning by doing" model, frequently discussed in education literature, underscores its widespread use in project courses (Green, 2005).

In design studios, learning by doing involves activities where students develop a deep understanding of problems related to real-world or simulated products (Morgan, 1983). The immersive, active learning environment fosters creativity, problem-solving, and the integration of theoretical and practical knowledge essential to industrial design.

Actor-Network Theory

Actor-network theory (ANT) was developed in the 1980s by Bruno Latour, Michael

Callon, and John Law as a framework to analyze and decipher complex social networks consisting of multiple variables and their subcomponents, all of which continuously influence one another and the system as a whole. One of ANT's defining features is its structuralist perspective. Rather than relying on essentialist explanations such as "what is true is inherently correct, and what is not proven as correct is inherently false," ANT accepts entities and phenomena as they are, seeking to objectify and equalize them for analytical purposes to explore the outcomes of their interactions (Latour, 1999).

ANT challenges previous theories like "social analysis theory," which focus solely on human agency while disregarding non-human elements (e.g., objects, technologies, systems) and invisible actors (agents), deeming these theories inadequate for explaining complex social networks. ANT considers humans and non-human entities as equal participants in their capacity to influence systems and one another. Objects and phenomena are viewed as co-constructors of social structures (Latour, 2008). Humans are defined as "actors," while non-human entities are termed "actants," signifying their capacity to act (Fallan, 2010). Latour emphasized that "nothing can be reduced to something else, but everything can relate to everything else," rejecting reductionist approaches and focusing instead on the relationships among entities (Latour, 1984).

In ANT, non-human actants are not passive "objects" under human control but active participants that shape and constrain human actions. This approach critiques modern epistemology for sidelining the formative influence of non-human actors while privileging human agency (Harman, 2009). ANT highlights that non-human entities are not merely shaped objects or planned stages; rather, they actively influence human actions (Çelikel, 2013).

Latour's objection to separating humans and objects stems from his goal of bridging the gap between material (world) and conceptual (word) realms, represented by the terms "actor" and "actant." Latour argued that neither humans nor objects have inherent superiority over the other in their capacity to act (Latour, 2008). Similarly, Appadurai's concept of the "social life of things" posits that objects, like humans, have a lifecycle, biography, and social existence (Appadurai, 1986). Beyond the core concepts of actors, actants, and agents, ANT introduces "intermediaries" and "mediators." Intermediaries facilitate interactions within the social network by enabling and accelerating the spread of relationships but remain unaffected by those interactions themselves. Mediators, by contrast, actively influence and shape the interactions they facilitate (Latour, 2008).

Another key concept in ANT is "translations," referring to the delegation or transfer of tasks and authority from one actor or actant to another. This process involves four key stages, as outlined by Latour (1995):

Problematisation: Defining the source and structure of the issue among the actors and actants.

Interessement: Inviting other actors or actants to join the social network and delegating authority to them.

Enrollment: Establishing procedures and relationships among the participating actors and actants.

Mobilization: Encouraging passive actors to take action through the facilitation of privileged actors acting as mediators.

Black Box Theory

The systems analyzed using ANT often involve highly complex social or technical networks, which can become even more convoluted when subcomponents of actors and actants are considered. This complexity may contradict ANT's goal of simplifying and deciphering these networks, potentially diverting focus from critical points of analysis. To address this, ANT is frequently used alongside Black Box Theory.

The Black Box Theory, employed across disciplines such as psychology, marketing, politics, software engineering, and other engineering fields, conceptualizes systems as "black boxes." It focuses on the system's inputs and outputs rather than its internal structure. This theory was developed in the 1960s by Norbert Wiener and Mario Bunge, building on earlier guidelines proposed by Wilhelm Cauer for analyzing electronic circuits (Bunge, 1963).

The Black Box Theory examines how a given entity interacts with external macro-environments, emphasizing that these interactions are influenced by the nature of the entity or the actors that designed it (Harman, 2009). In the context of industrial design project courses, unless a problem emerges from the actors or actants within the social network, the internal mechanisms remain closed, focusing solely on the communication networks. If an issue arises, the internal structures are reanalyzed and redesigned to resolve the problem and generate new inputs and outputs.

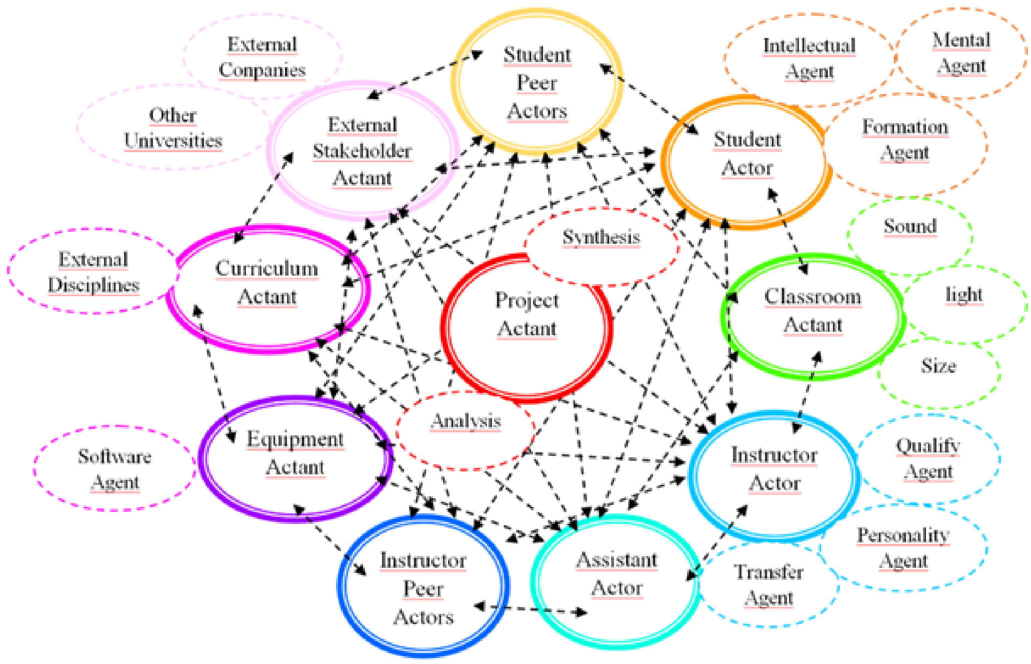
Project courses, forming the backbone of industrial design education and simulating professional design studios, are characterized by their complex, multi-component social and cultural networks.

To analyze the explicit and implicit aspects of these courses and their interrelations, ANT serves as a structural framework, while Black Box Theory offers a methodological lens for focusing on key variables.In the design studio, human variables are designated as actors; visible, non-human variables as actants; and hidden but influential variables—revealed through the Black Box approach—as "agents."

At first glance, the design studio appears as a physical classroom with a design instructor ("lead actor"), a teaching assistant ("assistant actor") bridging the gap between the instructor and students, a design student ("student actor"), other students ("peer actors"), and the equipment used in the project, such as laptops, drawing tools, and presentation boards ("equipment actants"). Hidden variables discovered through the Black Box approach are labeled as agents. Figure 1 illustrates the network of actors, actants, and their communication channels within the design studio, viewed as a social network structure. In industrial design studios, all actors, actants, and agents continuously influence each other and the system as a whole. These interactions occur through "communication networks," a term more aligned with ANT terminology. Before exploring these networks, the necessary actors and actants are identified and analyzed using the Black Box Theory to uncover hidden agents. This combined approach ensures that problems within the design studio are identified, analyzed, and addressed effectively while maintaining focus on the interplay of explicit and implicit factors within the studio environment.

Figure 1

A diagram illustrating the actors and actants that constitute the social network structure in a project-based course.



Project Actant: In design education, project-based courses are conducted around a defined topic. Each student actor begins the project process by selecting a specific sub-project topic in collaboration with the directing actors.

At this point, whether the sub-project topic aligns with or diverges from the inclinations of the student actor and the directing actors can influence the project process. As mentioned earlier, the intellectual background and experiences accumulated by both actors up to that point are considered to significantly impact the process. Here, as an actant, the topics and project briefs that design students work on, as well as the complex and interrelated processes from the presentation of these topics to the defense and evaluation of completed design projects before a jury, are examined. Figure 2 demonstrates the product development processes in industrial design project courses, with design processes deciphered through the black box methodology by gradually unveiling the black boxes and reaching the sub-black boxes.

Figure 2

A diagram illustrating the actors and actants that constitute the social network structure in a project-based course.

Student Actor: During the course, the student actor engages with the project they are working on, receiving critiques from the instructor. They bring to the table all their accumulated experience, skills, and intellectual capital. Since the student actor builds all cognitive and creative actions in the project processes on their pre-university intellectual foundation, it is understood that intellectual richness significantly influences creativity. The environment in which the student actor was raised, the quality of their previous education, their interests, accumulated knowledge, skills, and tools collectively impact their perceptual capacities, including imagination and creativity, during the project course. If it is assumed that all the intellectual accumulation the student gathered before their undergraduate education is reflected in the design studio, this phenomenon can be considered as an “intellectual capital agent.” In industrial design departments, support courses are offered before project courses to equip student actors with the knowledge and skills required for their projects.

When these courses, often borrowed from external disciplines, are revised according to the characteristics of industrial design and delivered using examples from the field, it is believed that assimilating this knowledge and skillset through “learning by doing” principles will support student creativity during the execution of project courses. This observation of transformation in student actors during the process can be evaluated as a “formation agent.” The different mental structures of students manifest at various stages of the project process, resulting in either stagnation or adept problem-solving, referred to as the “mental agent.” Due to differences in the prior knowledge and skills of student actors, their starting levels in the studio vary, leading to differing rates of acquiring design skills as semesters progress. These differences, observable as varying levels of design skill acquisition among students in the same studio, act as agents influencing the entire system.

Instructor Actor: In shaping the cultural environment of the design studio, the instructor actor, present as the design studio instructor, plays a key role. Like student actors, instructor actors are not homogeneous among their peers. Each instructor carries unique characteristics that distinguish them, forming the “personal trait agent.” These traits can be categorized into “skill agent,” “transfer agent,” and “character agent.” The instructor actor’s behavior typologies emerge during the project processes and impact other actors and actants, earning them the title of “behavior agent.” These behaviors, whether directly or indirectly, can influence the morale and motivation of student actors within the reciprocal and continuous interaction of the studio culture. Beyond teaching and learning, instructor actors undertake the crucial role of fostering creative thinking and promoting lifelong learning among students. The ability of instructor actors to fulfill these roles depends on their capacity to create an environment of dialogue and consultation that sparks curiosity and encourages creative and critical thinking in student actors.

Assistant Actor: Graduate students pursuing advanced degrees in industrial design and participating in courses to gain teaching experience as prospective instructors are referred to as assistant actors. Assistant actors share the teaching load of instructor actors and provide support to both instructor and student actors.

While the characteristics described for instructor actors are also applicable to assistant actors, assistant actors often lack the teaching and instructional experience of instructor actors due to their relatively young age. However, their close age proximity to student actors can facilitate communication, turning this into an advantage. Having recently been in the role of student actors themselves, assistant actors may exhibit greater empathy, bridging the gap between instructor and student actors.

Instructor Peer Actors: These actors vary across institutions and are involved in project processes in different capacities. In some institutions, various instructor actors rotate within a classroom system to contribute to student projects, while in others, each instructor oversees the project processes of their group within a group system. Regardless, peer instructor actors influence the entire system by playing roles in defining project topics and educational strategies at the beginning of the process and serving as jurors evaluating projects—including those outside their groups—at the end.

Student Peer Actors*:* During project courses, student actors receive critiques from instructor and assistant actors as the project processes unfold. Meanwhile, other students participate as student peer actors, either actively or passively listening within the studio organization. Collaboration or competition among these actors influences the overall system and its components.

Classroom Actant: The physical spaces where courses are conducted are referred to as classroom actants. The characteristics of classrooms, including acoustic, thermal, lighting, and spatial ergonomic compatibility, as well as access to resources like food, rest, computers, the internet, and necessary equipment, impact all actors, actants, and the overall system. The conditions of this actant affect educational, scientific, and social activities, including collaborative group work, jury arrangements, and the presentation, defense, and evaluation of projects.

Equipment Actant: The tools and materials used by student actors during the research, visualization, and presentation stages of project processes, such as computers, tablets, smartphones, drawing boards, rulers, and coloring tools, are considered equipment actants. Hidden elements like computer-aided design software, artificial intelligence applications, and internet tools, which emerge to influence all components and outputs within the system, can be seen as “software agents” embedded within equipment actants.

External Stakeholder Actant: Institutions outside the physical boundaries of the design education institution, yet capable of infiltrating and influencing the social network structure of project courses through their actions, are defined as external stakeholder actants. Though they involve human actors when unpacked, they are treated as actants due to their corporate nature. Examples include other universities’ industrial design departments. In Turkey, department heads and vice-chairs of all universities offering industrial design convene annually to discuss national design education, curricula, professional organizations, and relationships with companies, forming various strategies. These meetings, where they observe each other's educational environments and student outputs, indirectly influence project courses.

Therefore, such interactions with external stakeholders are referred to as "institutional education agents." Additionally, companies involved in commercial activities often engage with project courses, especially in the final semesters, by contributing topics for product design. This collaborative interaction, also termed "university-industry cooperation," directly influences the actors and the overall education, enhancing the previously mentioned simulation characteristics of the course. These institutions are identified as "external company agents."

Analysis of Communication Networks Between Actors, Actants, and Agents in Project Courses Using the Actor-Network Theory Approach

Student Actors' Interaction with Themselves: In project development processes, the healthy interaction of the student actors with themselves is considered to positively influence all actors, actants, and the overall system. To establish a solid foundation in their self-relationship, student actors are expected to possess or develop the following skills: time management, adaptability to various conditions, openness to constructive criticism, self-reflection, the ability to identify weaknesses in their design skills, and development strategies to strengthen them, recognition of their strengths to establish a unique design style, self-monitoring of personal growth, enjoyment of learning and self-improvement throughout the educational stages, logical risk-taking, and self-motivation. Actors with high intrapersonal intelligence are more likely to build healthy relationship with themselves, enabling proper self-consultation, decision-making, and self-regulation. Therefore, this interaction can be defined as a "self-regulation network."

Student Actor's Interaction with Instructor and Assistant Actor: The guidance of instructors and assistants, who themselves are industrial designers, plays a pivotal role in transforming student actors into industrial designers during project courses. The understanding, process mastery, skills, and competencies required by the industrial design profession are often assimilated through years of experience by instructor actors, becoming implicit and embedded knowledge.

The transfer of tacit knowledge in creative disciplines like design differs significantly from the explicit knowledge transfer in fields like engineering. Furthermore, the contrasting nature of engineering problems—structured and solvable through systematic formulas—and the complex, ill-defined design problems necessitate different educational approaches.This distinct educational dynamic necessitates closer collaboration between instructor and student actors compared to the traditional teacher-student relationship in engineering education. The communication channel between them resembles a highway where work is presented, defended, critiqued, appreciated, approved, rejected, or redefined with new suggestions. A wide and smooth highway indicates efficient communication and information flow, while a narrow and congested one signifies slow or blocked communication. The instructor actor's ability to maintain a balance of humility and dignity, communicate positively and moderately, provide feedback without undue stress, calm anxious students, act fairly, honor achievements, and behave consistently and respectfully can broaden this communication channel. Consequently, it is predicted that high social intelligence in both actors positively influences this relationship and the system as a whole.

Instructor Actor's Interaction with Student Peer Actors: Although design critiques in project courses primarily occur one-on-one, other students, identified as peer student actors, participate in the class as active or passive observers while waiting for their turn. Thus, a project group can be considered a social, cultural, and public space. Even though critiques are directed at the students presenting their project, the instructor actor expects peer actors to listen, understand, and apply general and specific feedback to their projects.

Student Actor's Interaction with Peer Student Actors: In project groups, knowledge and skills often circulate among students, becoming fluid and sometimes tacit, effectively transforming students into instructors for one another. After receiving feedback from the instructor, a student actor may also seek additional critiques from their peer student actors. This interaction enriches the student actor's understanding of the instructor's feedback through the perspectives of their peers. In some institutions, educators cluster project groups for collaborative work. This approach aims to prepare designers for interdisciplinary collaboration by fostering habits of working with diverse individuals and disciplines. However, it has been observed that student actors working with self-selected peer actors often achieve more productive results than those grouped by instructor actors.

Instructor Actor's Interaction with Peer Instructor and Assistant Actors: In project courses, alongside instructor actors, assistant actors and peer instructors managing other project groups collaborate within institutions. However, peer instructors work more closely together during the initial discussion of project topics, department meetings, and end-of-semester project juries. During this intense collaboration, the behavior of instructors and assistants toward one another is observed by student actors. Negative interactions among colleagues can adversely affect student motivation, undermining their respect for and trust in the instructors and the institution. Therefore, respectful communication between instructor actors, peer instructors, and assistant actors is deemed critical for positively influencing all actors and the system.

Conclusion

This study aimed to shed light on the complex network of visible and invisible factors within project courses, which simulate the product development processes of professional industrial design services and serve as the cornerstone of industrial design education. By revealing and analyzing these factors, the study sought to provide a clear and detailed picture of the perceived chaos in project courses, contributing to future efforts aimed at improving structure and organization. Actor-network theory (ANT) and Black Box Theory, along with their terminologies, were utilized as tools to decipher and structure these intricate social networks.

The study captured the relationships among actors, actants, and agents—typically unnoticed during smooth system operation but only visible when significant problems arise—through a real-time snapshot of the functioning system. This analysis revealed parallels between the logic patterns observed in this research and the findings of ANT and Black Box Theory applications in other disciplines, such as sociology, politics, biology, electronics, and the internet. These alignments suggest that the study successfully achieved its objectives.

By adapting a well-established observational methodology from other disciplines to industrial design education—specifically project courses—this research offers significant contributions to the literature. It highlights unseen factors linked to ongoing or potential process issues, thereby enriching the understanding of project courses. As with any academic study, this research has limitations. Chief among them is the reliance on the researcher's personal experiences and observations, informal discussions with colleagues at different institutions, and past academic activities not conducted explicitly for this study due to time constraints. Future research encompassing a broader sample set, including industrial design departments in universities across different countries, could provide a richer conceptual framework by exploring how diverse contexts, sociologies, and cultures reflect in design studios. In this regard, this study is expected to make a valuable contribution to the literature on industrial design education and inspire future research.

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Advanced Coating Technologies: Thermal Spray, Physical Vapor Deposition, Chemical Vapor Deposition, and Sol-Gel Applications

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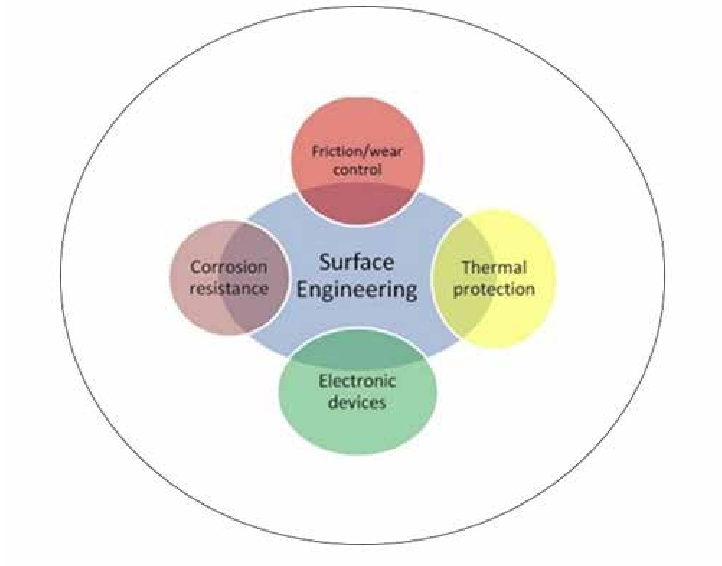
Introduction

Importance of surface engineering

In recent years, there has been significant progress in the advancement of methodologies for surface protection, with the primary objective of ensuring optimal preservation of substances. The selection of protection is dependent on the surrounding environment, the conditions of utilization, and the compatibility with the substrate's material. A multitude of surface treatment methods have been proven to be efficacious for protecting surfaces and achieving other operational objectives, and these methods are already in industrial use (El-Awadi, 2023). The term "surface engineering" refers to the methodical design of engineering components with the objective of enhancing their performance within operational contexts. This objective can be realized through surface treatments, which have the capacity to generate combinations of surface and bulk properties that are not attainable in a single material (Gawne, 1993). Surface engineering is a multidisciplinary topic that encompasses numerous branches of science related to materials science, chemistry, and physics. The present focus of multidisciplinary teams is on the research and advancement of innovative materials and coatings, with the goal of augmenting their mechanical, electrical, electrochemical and antibacterial characteristics (Rokosz, 2022). As illustrated in Figure 1, the applications of surface coatings are evident.

Figure 1

The utilization of surface engineering in diverse disciplines (Prashar et al., 2020).



Surface engineering can be broadly categorized into two main approaches: physical and chemical. Physical techniques are defined as the utilization of heat or energy in order to modify the surface. The following are examples of such techniques: thermal spray coatings, chemical vapor deposition (CVD), physical vapor deposition (PVD), and laser surface engineering. It is evident that these techniques offer significant versatility in the tailoring of surface properties. This includes, but is not limited to, hardness, adhesion, and surface texture. Consequently, they have the capacity to meet specific requirements. In contrast, a range of chemical techniques have been shown to offer a means to control surface deposition and modify the material chemically. Examples of these techniques include electroplating, electroless plating, sol–gel coatings and chemical etching. It has been evidenced that this process can lead to enhancements in a number of areas, including corrosion resistance, biocompatibility and functionalization. Surface engineering is crucial to industry. It enhances performance, protects materials against the environment and develops functionality. Considerable progress has been made in the field of surface engineering. However, challenges persist due to complex processes, precise parameter control and scalability issues for large-scale production. A number of other considerations must be taken into account, including the integration of surface engineering with other fabrication techniques and the question of cost-effectiveness. Emerging trends and technologies hold promise. The employment of sophisticated computational modelling and simulation techniques has the capacity to expedite the conceptualization of engineered surfaces that demonstrate customized properties. The exploration of new materials, such as graphene, opens up possibilities for advanced coatings and functionalized surfaces (Ramezani et al., 2023).

In order to comprehend and appraise the efficacy of surface engineering processes, a range of characterization methods is utilized. The application of microstructural characterization methodologies, incorporating scanning electron microscopy, X-ray diffraction, and transmission electron microscopy facilitates the exploration of surface morphology, phase composition, and crystallographic structure. The analysis of surface topography can be facilitated by a variety of instruments, including atomic force microscopy (AFM), scanning tunnelling microscopy (STM), and surface profilometry. The utilization of these instruments facilitates the accurate measurement and visualization of surface characteristics, including but not limited to roughness, texture, and feature dimensions. Mechanical and tribological characterization methodologies (e.g. hardness, wear and friction, scratch and indentation testing) reveal how surfaces perform mechanically. (Ramezani et al., 2023). In this context, coating technologies represent a significant application area of surface engineering.

Coating technologies and their classification

The field of tribology and wear protection of coatings has seen considerable research activity and rapid progression in recent years. The impetus for this development has chiefly arisen from the advent of innovative coating materials, structural configurations and manufacturing technologies. The evolution of coating techniques has been a gradual process, with various methodologies being developed over the course of several decades. In conclusion, it is evident that coating technologies constitute a pivotal component within contemporary manufacturing, offering a wide variety of applications across various industrial sectors. It covers and involves many research fields. Continued innovation within the field of coating technology, driven by advancements in coating materials and deposition methods, is anticipated to have a transformative impact on industry and academia alike, giving rise to novel products and applications. It is therefore vital that investigation and advancement in this domain is pursued in the future; any significant advance in this area will merit close attention from all research communities. (Ma, 2023).

The field of coating technology represents a significant and encouraging area of research in the domain of surface engineering, with considerable potential for application in future industrial contexts. The development of coating techniques has resulted in coatings becoming an integral component of industrial manufacturing. These coatings possess a range of advantageous properties and characteristics, including super hydrophobicity and self-cleaning capabilities, augmented biological antibacterial properties, and enhanced corrosion resistance (Chen et al., 2024).

Evidently, the utilization of coating has undergone a significant transformation, becoming a pivotal technique for enhancing the efficiency and value of materials. The process of surface coating is both reliable and cost effective. It finds application in the fabrication of various instruments, materials, and components of machinery. The requirement for the desired surface properties, including resistance to corrosion, erosion, and wear, is pivotal in this process. The primary objective of coating application is typically categorized into two broad categories: decorative and functional. The enhancement of surface characteristics, including adhesion, erosion, corrosion and wear resistance, can be achieved through the utilization of functional coatings. In the contemporary era, a plethora of coating methodologies are employed to attain the desired functional or decorative characteristics (Pattankude & Balwan, 2019).

The process of applying a coating to an object surface is known as ‘coating’, with the object itself being designated as the ‘substrate’. The coating may be applied in a manner that ensures comprehensive coverage of the substrate, or alternatively, the substrate may be coated in a selective manner, with specific regions of the substrate receiving the coating and others remaining uncovered. Coating may be delineated as the application of a protective layer to the surface of an item. The application of coatings is a common practice that is employed for the purpose of modifying the surface characteristics of the substrate. The overarching goals of the process are threefold: firstly, to modify the substrate’s appearance; secondly, to enhance adhesion; and thirdly, to augment corrosion resistance and improve wear and scratch resistance. Industrial coatings are defined by their function as a protective barrier rather than their aesthetic properties. Nevertheless, it is imperative to acknowledge their capacity to confer aesthetic value. The most common materials utilized in the domain of industrial coatings include ceramic, Al_2O_3, acrylic, polyester, polyurethane, epoxy and silicone (Pattankude & Balwan, 2019).

A plethora of coating methodologies and materials are at one’s disposal to suit diverse coating applications, with a shared objective of safeguarding parts or structures against the detrimental effects of mechanical or chemical damage. One advantage of this protective function is that it engenders a decrease in manufacturing costs, since the fabrication of new parts is not required. Nonetheless, coating methods have a role in specific applications, depending on the desired functionality. The most significant applications are protection against corrosion and wear. It is vital to recognize that, despite the plethora of available processes, only a limited number of these have been proven to be effective and applicable in the field. The most notable methods comprise the following: PVD, CVD, thermal spray, sol–gel processes, micro-arc oxidation, and polymer coatings. The suitability of each method is dependent upon the desired application, with the options available including varying deposition methods, materials, second phases, thickness, and densities. The selection of materials is paramount to the success of coating, as they provide protection. It is acknowledged that a wide variety of materials, encompassing those of metallic, ceramic and polymeric nature, can be employed to form a protective layer (Fotovvati et al., 2019).

The engineering components have been utilized in a variety of applications, encompassing, but not restricted to, the domains of aircraft, power generation, the marine industry, the chemical industry and the paper industry. These components have demonstrated a high degree of reliability when employed in a range of extreme environmental conditions. The principal concerns that emerge in the context of performance wear, such as corrosion and erosion, or their combinations, result in a reduction in the components' service life. Coating techniques are utilized to prevent surface degradation through either overlay or diffusion processes, with compositions tailored to meet specific functional requirements. A plethora of coating methodologies are at one's disposal for the purpose of averting the deterioration of surfaces (Pradeep et al., 2022).

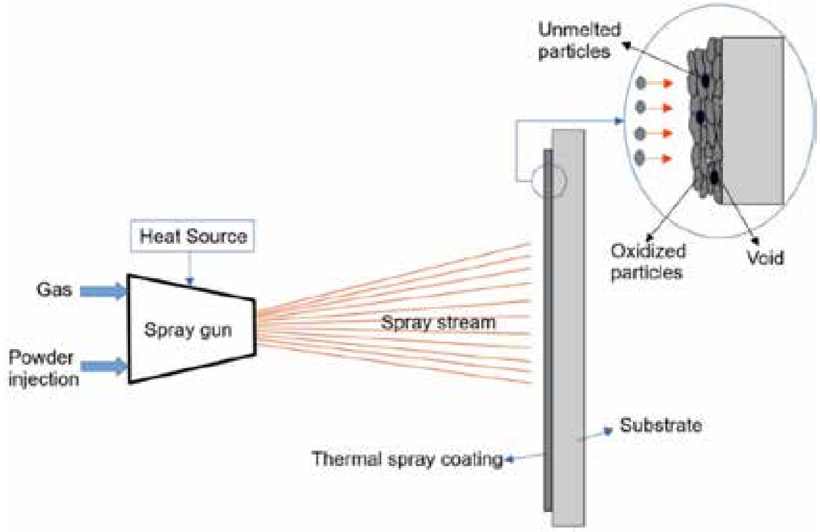
The present study examines the coating methods in question in terms of their basic principles, materials used, application areas, and advantages and disadvantages. The aim of the present study is dual: initially, to provide practical information for engineering applications, and secondly, to furnish in-depth technical content for researchers. Consequently, the current study makes a notable contribution to the advancement of the field, facilitating the selection of suitable advanced coating technologies and ensuring their effective application.

Thermal Spray Coating

Thermal spray processes constitute a significant and rapidly expanding category of surface modification technologies. A broad range of solid feedstock materials is employed, encompassing metals and alloys, hard metals, ceramics, and polymers, predominantly in the form of particulate matter, wires, and suspensions. Hard metals constitute a substantial category of materials that undergo processing by thermal spray processes in order to be applied as coatings. The formation of coatings is contingent on plastic deformation of the feedstock particles at the instant of impact, which is preceded by acceleration within or without the spray gun. The majority of thermal spray processes are accomplished through the partial or complete melting of the feedstock material. During the spraying process, the substrate remains unmelted. The splats adhere to the substrate primarily through mechanical bonding. The utilization of thermal spray technology facilitates the realization of the functional properties of hard metals on the surface of large components, which are not feasible through powder metallurgy processes due to technical and economic constraints (Berger, 2015). Figure 2 provides a schematic representation of the thermal spraying technique.

Figure 2

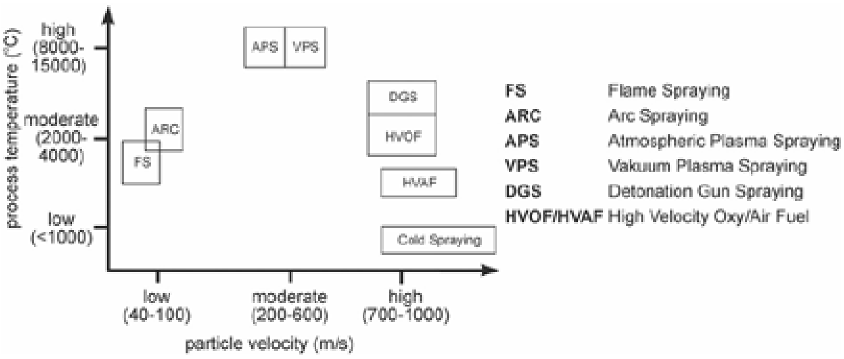
Schematic depiction of the thermal spray coating process (Ramezani et al., 2023).



A plethora of materials are utilized in thermal spray processes for the purpose of developing coatings on solid substrates that demonstrate resistance to elevated temperatures. Thermal spray coatings characteristically possess a rough and porous texture. In comparison with conventional surface treatment technologies, they exhibit enhanced reliability, particularly with regard to mechanical properties and their applications in protection. Thermal spray processes are classified based on their energy source (electrical or chemical) and are employed in a variety of fields (aviation, energy, medicine, marine etc.) to develop coatings with different properties. In the field of additive manufacturing, specific thermal spray methodologies have proven effective in the creation of standalone components and the remediation of damaged elements. The high-velocity techniques of HVOF (High-Velocity Oxygen Fuel) and HVAF (High-Velocity Air Fuel) are characterized by their classification as high-velocity techniques, in conjunction with moderate temperatures ranging from 2000 to 4000 °C. Conversely, cold spray technology is contingent on the mechanical deformation characteristics of metallic powders operating at low temperatures, often below 800°C and approaching recrystallisation temperatures. It is mostly used on ductile materials. In contradistinction, plasma spray is a high-temperature process that has been demonstrated to yield dense coatings. This method is highly applicable to ceramics. Arc and Flame Spray (FS) are relatively slow processes. Arc can produce large throughputs/thick coatings. Thermal spray processes are also used for surface repair, rebuild, and clearance control, as well as to change the friction factor. Manufacturing items like prostheses and gas turbines heavily rely on thermal spray technologies. For example, plasma spray is used to apply hydroxyapatite ceramic coatings for bone bonding on prostheses. The utilization of thermal barrier coatings is of paramount importance in the context of high-temperature operations, wherein their function is to ensure the effective management of clearance within gas turbines. It is evident that thermal spraying is employed in a variety of materials (Guduru et al., 2022). The various thermal spray processes can be delineated in relation to parameters such as particle velocity and process temperature, as demonstrated in Figure 3. (Berger, 2015)

Figure 3

Schematic depiction illustrating the interrelation between process temperature and velocity for the various spray processes (Berger, 2015)

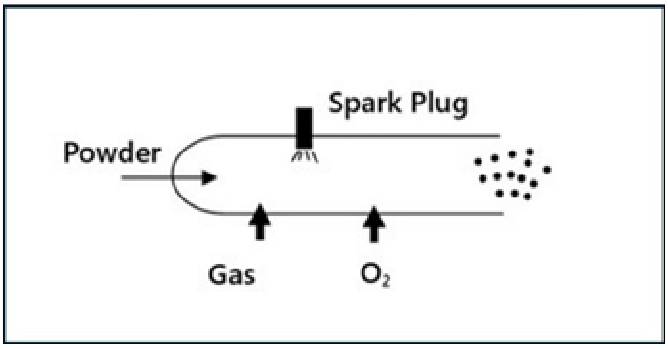


Various thermal spraying processes

A. Detonation Gun: Gas detonation has been evidenced as a means of producing optimal levels of velocity, pressure, and density within the gas flow, thus outperforming other spraying techniques in these regards. Consequently, the coatings resulting from this process are distinguished by their markedly high density and microhardness, in addition to their low porosity. It is evident that the aforementioned properties render the coatings optimal for utilization in scenarios necessitating the most stringent quality standards. For instance, they are particularly well-suited to the fabrication of aircraft engine components. The process of coating materials onto the substrate surface using the detonation gun (D-gun) involves the combustion and subsequent expansion of the fuel (normally oxygen and acetylene) to generate a jet which, in turn, melts and propels the coating materials. The initiation of detonation is affected by the spark ignition of gas in a gun. This procedure is distinguished by its comparatively reduced operational expense when juxtaposed with more prevalent HVOF and plasma spray methodologies. Within the specified parameters of the configuration, the gases are introduced into the chamber of combustion at a pressure that is marginally higher than the standard atmospheric pressure. The overarching objective of this process is to deposit coatings with a thickness of approximately 250 µm or less, with a view to enhancing the wear resistance of components that are subjected to extreme service conditions (Talib et al., 2003). As demonstrated in Figure 4, this occurrence can be observed empirically.

Figure 4

Detonation Gun (Talib et al., 2003).



B. Atmospheric plasma spraying (APS): The APS process employs thermal plasma as the heat source for the deposition process. These plasmas are produced by means of direct current arc or radio-frequency discharge. It has previously been established through empirical observation that such conditions permit temperatures in the flames to exceed 8,000 K, with peak values of up to 14,000 K at the jet core. The velocities of particles range from 20 to 500m/s, contingent upon the distribution of the particles' sizes. The elevated temperatures of the process cause a significant percentage of the material to melt, which, in combination with the comparatively high velocities, results in the production of coatings that exhibit superior deposition densities, bond strengths and reduced porosity when compared to the majority of thermal spraying processes. The utilization of APS has been demonstrated to yield coatings that exhibit a high degree of cost-efficiency and quality. This facilitates their successful implementation in multiple industrial domains (Tejero-Martin et al., 2019).

C. Vacuum plasma spraying: The development of plasma spraying in controlled environments can be traced back to the late 1960s, with the primary objective of mitigating the deleterious effects engendered by the interaction of the in-flight heated particulate matter in the surrounding environment. Such adverse effects comprise oxidation and unwelcome contaminants in the coatings. The employment of low and very low pressures has been evidenced to be conducive to the advancement of thermally sprayed coatings of a high quality. The pressure levels employed in these processes vary considerably. In the case of low-pressure plasma spraying (LPPS), pressures are typically in the range of 4,000 Pa to 40,000 Pa; however, in the domain of very low plasma spraying (VLPPS), pressures can reach as low as 100 Pa. In the event of a value falling below this threshold, the designation employed is that of vacuum plasma spraying (VPS). This approach has been evidenced to produce coatings with porosity levels as low as 1%, exhibiting columnar structures comparable to those attained through physical vapor deposition (PVD). Moreover, it has been established that this method engenders an enhanced deposition rate in comparison with PVD techniques (Tejero-Martin et al., 2019).

D. Cold spraying: The process of kinetic or cold spraying, as the nomenclature suggests, is predicated on the transfer of elevated levels of kinetic energy into the constituent particles of the feedstock. The purpose of the process is to achieve the required bond strength upon impact at the surface of the substrate. This is an antithetical phenomenon to the customary usage of heat transfer evident in alternative thermal spray technologies. The process under discussion allows deformable powder particles of a ductile nature to be deposited without the need for the conventional melting process, followed by a rapid impact step, with subsequent solidification of the resultant material. This method of powder deposition effectively reduces residual stresses and also reduces the incidence of in-flight oxidation of the particles. The fundamental principle of the process entails the utilization of pressurized gases with diminished oxidation potential, such as helium or nitrogen. The gases are exposed to moderate heating, typically below the melting point of the feedstock particles (up to 1000K), in order to enhance gas flow velocities, as opposed to heating the particles themselves. Once the required pressure and temperature conditions have been met, the gas is guided through a de Laval nozzle, thereby accelerating it to velocities that surpass the speed of sound (up to 1,200 meters per second) as it undergoes an increase in temperature during the process of expansion. It has been deduced that this process facilitates the achievement of temperatures that are lower than ambient temperature on occasion. The resulting coatings exhibit the same phase content as the powder feedstock, devoid of oxide contamination and characterized by low porosity. The coatings demonstrate a propensity for compressive residual stresses, a notable deviation from the tensile stresses typically observed in other thermal spray technologies. Additionally, the coatings exhibit low ductility, a consequence of the extensive work hardening that occurs during the deposition process (Tejero-Martin et al., 2019).

E. Flame spray: Flame spraying is an industrial process that has existed for over a century, during which time its technology has remained relatively unchanged. In essence, the process involves the injection of oxygen and fuel (acetylene or propane) through a nozzle. The combustion of the gaseous mixture occurs prior to the occurrence of a flame by the nozzle. The flame temperature fluctuates within the range of 3000 to 3300 °C, contingent upon the oxygen-to-fuel ratio. The feedstock materials utilized can be in powder or wire form. The process under discussion involves the deposition of materials such as nickel- and cobalt-based alloys, certain refractory metals, ZrO_2, Al_2O_3, TiO_2, and Cr_2C_3, all of which are deposited in a NiCr matrix. The spray process is adaptable, portable, and has a low capital cost. The implementation of this methodology is a prevalent technique in the synthesis of coatings characterized by elevated levels of porosity. As demonstrated in previous research, the flame spraying process has been shown to require less energy and to be more economical than other thermal spray processes. Nonetheless, it has been shown to lack corrosion resistance. Conversely, the pre-oxidized portion exhibited no discernible response to air oxidation. The porosity of the finishes exhibited a marginal effect on the oxidation of the air. It has been proven that elevated levels of in situ oxides and pores in flame-sprayed coatings have a deleterious impact on the efficacy of the process when it is employed in high-temperature applications (Qadir et al., 2024).

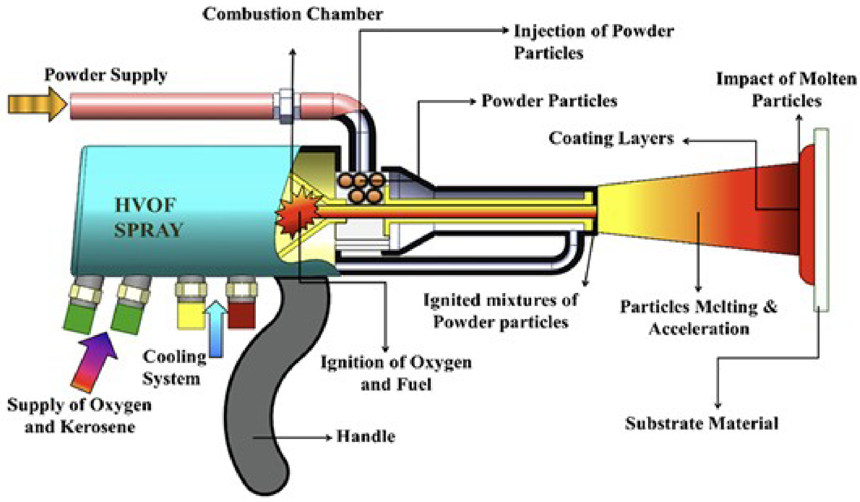
F. Arc Spray: Arc-Spray (Wire-Arc) involves the utilization of direct current arc between two conducting wires for the purpose of melting consumable wires. The wires in question are found to be electrically charged, exhibiting opposing polarities. They are then fed into the arc gun. The wires are motorized and fed into the spray torch. It has been established through documented evidence that the presence of opposing charges on the wires has the capacity to generate sufficient heat to cause the melting of the wire tips. This phenomenon is a consequence of continuous exposure to the heat generated. The subsequent process of atomization, involving the use of gases such as air, argon and nitrogen, propels the droplets towards the substrate surface. This process has been demonstrated to exhibit higher deposition rates in comparison to HVOF and plasma spray (Talib et al., 2003).

G. High-Velocity Oxy-Fuel (HVOF): In the HVOF coating technique, the particles are initially dispersed into a stream of combustion gases, whereas they are subsequently sprayed and deposition occurs onto the surface of the base material. The fabrication of this HVOF spray gun was undertaken with the specific purpose of withstanding the multiple shocks that are typically present during the combustion process. Subsequently, the flame exits the nozzle, undergoes unimpeded expansion, and produces a supersonic jet characterized by elevated kinetic energy. The HVOF coating has the following properties. Firstly, it possesses low porosity and high hardness. Secondly, it exhibits strong adhesion due to its high impact particulate speeds. Thirdly, the process temperature is comparatively low when it is compared to the flame and plasma spraying process. Furthermore, HVOF spray methods have the capacity to deposit a variety of materials, including ceramic powders, polymers, composites, metals and alloys, such as Inconel, Tribo-alloy and Hastelloy. The HVOF technique is distinguished from conventional thermal spray deposition processes through its utilization of lower temperature heating and the discharge of powder molecules at extremely high velocity over the substrate to form coatings that are both thicker and more dense. As illustrated in Figure 5, the working principle of the HVOF thermal spray process is schematically represented.

HVOF coating techniques have a proven record of superiority over other thermal spraying techniques and are especially suitable for the application of cemented carbides and associated coatings. It has been demonstrated that high-speed particles impacting upon a substrate surface can lead to the formation of coatings exhibiting a high degree of density and uniform distribution. The presence of condensed splats is a hallmark of these coatings. The primary advantages of HVOF thermal spraying over other methods are its high particle velocity and relatively modest thermal energy dissipation during the spraying process (Sathish et al., 2023).

Figure 5

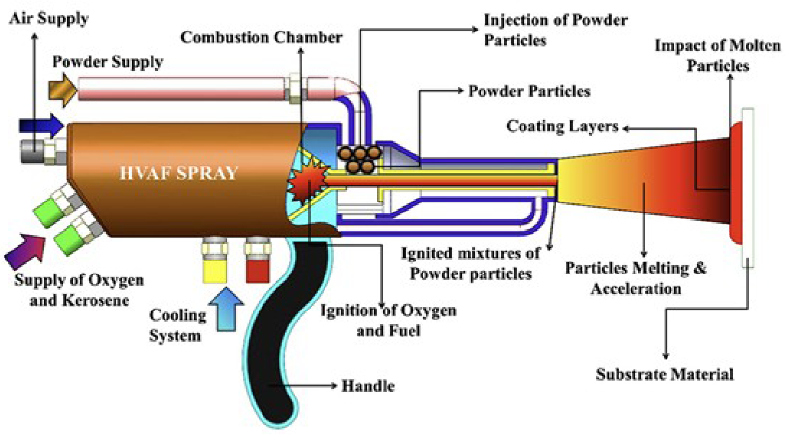
Schematic illustration of the HVOF thermal spray process (Sathish et al., 2023)



H. High-Velocity Air–Fuel Process (HVAF): The HVAF process represents a thermally sprayed coating approach that operates at a lower combustion temperature due to its utilization of compressed air. This method incorporates a streamlined design, obviating the need for water-cooling mechanisms, and consequently results in reduced running costs. It is within the combustion compartment that the HVAF process is initiated, with the objective of combusting a mixture of compressed air and fuel gas. The HVAF coatings process exhibited significantly superior adhesion properties in comparison to conventional spraying methods, thereby underscoring its efficacy in scenarios where bonding strength is paramount. The utilization of high-velocity spraying technologies, including HVOF and HVAF, has become a prevalent method for the application of hardened coatings. This approach functions as a substitute for the utilization of environmentally detrimental hard chrome, thereby contributing to the promotion of eco-friendly manufacturing practices. These hardened coatings possess wear-resistant properties and enhance the lifespan of the components, thus offering considerable benefits in the context of environmental production. The gas-fuel and liquid-fuel HVOF spray methods both employ the purest oxygen, resulting in a significantly higher ignition temperature in comparison to the HVAF spray process, which functions under highly compressed air. It has been ascertained that, due to the diminished oxygen concentration levels inherent to the HVAF process, the observed particles exhibit a substantially lower temperature in comparison to that of the conventional HVOF process. As illustrated schematically in Figure 6, the HVAF thermal spray process functions in the manner depicted. In the HVAF process, the temperature of the particulate remains below 1600 K. It is imperative to acknowledge that this is lower than the melting point of stainless steel. It has been hypothesized that controlled oxidation of the coating is an effective method of enhancing chemical homogeneity. In the HVAF process, the particle velocity is typically approximately 700 m/s, which results in minimal porosity and strong adhesion strength in the coating (Sathish et al., 2023).

Figure 6

Schematic view of working principle of HVAF thermal spray process (Sathish et al., 2023)



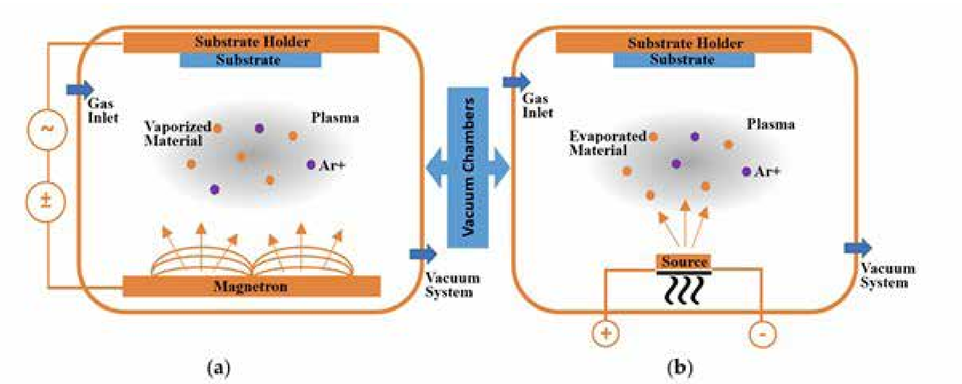
Physical Vapor Deposition (PVD) Coating

Physical vapor deposition (PVD) is described as the process of extracting atoms from a solid or liquid state via physical processes, which are then deposited on a nearby surface, leading to the formation of a thin film or coating (Gudmundsson et al., 2022). The process referred to as PVD is conducted under vacuum conditions. PVD processes encompass a variety of methodologies, including but not limited to electron beam physical vapor deposition, cathode arc deposition, ion plating, evaporative deposition, sputtering, and enhanced sputtering. The PVD method involves the evaporation of solid coating material using thermal or ion bombardment, the latter process being referred to as sputtering. Concurrently, reactive gas is also introduced, forming a compound with metal vapor and depositing a thin film of highly adherent coating on the substrate. Such coatings are utilized in a plethora of diverse applications. They include the following: the aerospace industry; the automotive industry; the surgical industry; the medical industry; dyes; molds for a range of materials; cutting tools; optics; firearms; textiles; and thin films. It has been established that all PVD methods are effective when it comes to coating surfaces facing deposition flux. The selection of the most appropriate deposition method necessitates consideration of various factors. These factors include, but are not limited to, the substrate type, the thin film material, the necessity for uniformity, and the requirement for thickness control (Shahidi et al., 2015)PVD has the capacity to produce dense and crystalline films at substantially reduced temperatures. It is particularly beneficial in configurations where the interdiffusion of elements between adjacent layers is detrimental and must be prevented. A notable illustration of this is provided by model systems employed to study interfacial phenomena. To illustrate, a sintering temperature of a minimum of 1400 °C is required to achieve the densification of screen-printed yttria-stabilized zirconia, whereas layers of comparable density are attained at 800 °C by PVD (Lobe et al., 2021).

The accumulation of coating materials in the form of molten or semi molten splats is an inherent property of thermal spray processes, a fact that is widely recognized within the scientific community. The processes of PVD are distinct from the thermal spray technology in that they construct a coating from the vapor phase at low environmental pressure (~10^{-4} mbar). The process of applying hot coating material necessitates elevated temperatures, thus ensuring that droplets do not solidify rapidly on a cold surface. The coating material is instead deposited onto the substrate from the vapor. This approach has yielded coatings that exhibit properties heretofore unattainable through conventional thermal spray processes. PVD coatings have been evidenced to manifest a high degree of homogeneity, characterized by a thin, dense, hard, and gas-tight composition. Alternatively, these coatings can be designed with a specially engineered microstructure, offering distinct advantages in specific applications (Von Niessen et al., 2010). The utilization of said techniques facilitates the extraction of particles from the designated target material under conditions of minimal pressure, thus enabling their subsequent conveyance and deposition on the substrate. The reactor utilized in the evaporation process necessitates elevated vacuum pressure levels. It has been established that these characteristics and parameters typically yield reduced atomic energy and diminished gas adsorption within the coating deposition. This outcome indicates that the movement of particles with larger grains leads to a noticeable decrease in the adhesion of these particles to the substrate compared to the sputtering technique. It has been established that during the process of deposition, contaminant particles are released from the melted coating material and subsequently move onto the substrate. The extant literature indicates that this phenomenon has the capacity to engender a diminution in the purity of the resultant coatings. Evaporation is typically utilized for the deposition of films and coatings of greater thickness, with minimal constraints imposed on the surface morphology. Nonetheless, it is imperative to recognize that the evaporation process exhibits enhanced deposition rates in comparison to the sputtering process. Consequently, the sputtering process is regarded as a viable option for applications where the surface quality is of paramount importance, with considerations such as roughness, grain size, and stoichiometry being of greater significance than the deposition rate. As has been shown, the deposition process is contingent upon the presence of certain temperature limitations in specific applications. It can be posited that this occurrence may be attributable to the generation of stress that transpires during the cooling process. The cooling process is dependent on the decrease in temperature or the substrate (polymer) melting point. This has resulted in the sputtering process becoming increasingly pertinent within the domain of PVD deposition techniques. Furthermore, innovative techniques derived from the sputtering process have been developed to address the constant increase in market demands. The advent of novel coating properties has been precipitated by the emerging of new systems derived from conventional processes, thus aligning with the requirements of both the market and researchers (Baptista et al., 2018). As depicted in Figure 7, the schematic representation of two traditional PVD methodologies.

Figure 7

Schematic representation of two traditional PVD methodologies: (a) sputtering and (b) evaporating utilizing ionized Argon (Ar+) gas (Baptista et al., 2018)



The capacity to demonstrate flexibility and adaptability in response to market demands has resulted in the development and refinement of techniques for a variety of processes. This has consequently resulted in the proliferation of multiple variants. These techniques are subject to constant evolution and continue to serve as a rich source of inspiration for numerous academic studies. A substantial corpus of literature, encompassing books and articles, has been published which disseminates information regarding these variants. This has resulted in a state of affairs in which it is challenging to quantify all extant techniques. PVD methods are the most frequently employed for the deposition of thin films, with sputtering and evaporation being the most common (Baptista et al., 2018).

Different types of PVD

A. Cathodic arc deposition: The process involves high-power electric arc discharge, which is directed towards the target (source) material, resulting in the blasting away of a portion of the material in the form of a highly ionized vapor that is subsequently deposited onto the workpiece (Shahidi et al., 2015).

B. Electron beam physical vapor deposition: In order to attain the requisite outcomes, the material to be deposited is exposed to an electron beam within a high vacuum environment. It has been demonstrated that this process results in a significant increase in the vapor pressure of the material. Following this process, the material is transported via diffusion and subsequently deposited by condensation onto the cooler workpiece

(Shahidi et al., 2015).

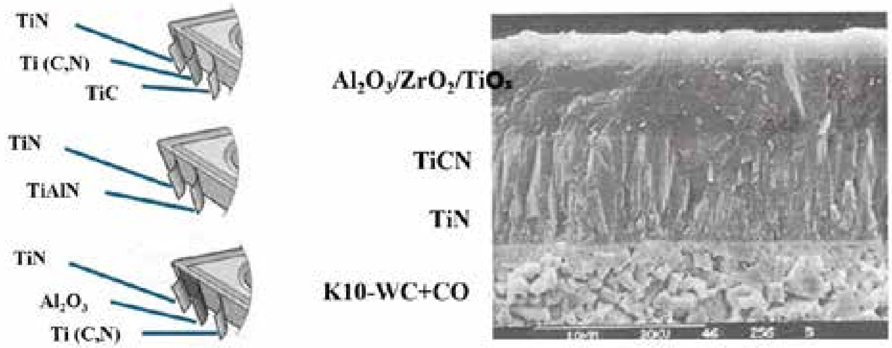
C. Evaporative deposition: The material to be deposited is exposed to an elevated temperature in a state of high vapor pressure, achieved through the utilization of electrically resistive heating within a vacuum characterized by a low pressure level (Shahidi et al., 2015). D. Pulsed laser deposition: The process involves the utilization of a high-power laser, which serves to ablate material from the target, thereby converting it into a vaporous state (Shahidi et al., 2015).

E. Sputter deposition: The plasma discharge, which is characterized by its tendency to emit a glow (and which is typically confined to the area around the "target" by means of a magnet), is responsible for bombarding the material, resulting in the sputtering of some of it away as a vapor for subsequent deposition (Shahidi et al., 2015).

PVD coatings applied to cutting tools offer significant advantages in terms of cutting accuracy, wear resistance, and surface quality. PVD coatings typically consist of hard ceramic or carbide compounds such as TiN, TiAlN, CrN, and AlTiN, which enhance tool wear resistance, thermal stability, and reduce friction coefficients. Coating thickness has been found to range between several hundred nanometers and several micrometers. It is worthy of remark that it remains stable at elevated temperatures; this property improves tool life, cutting force, and drilling efficiency during the machining of challenging materials, such as aluminum, hard metals, and stainless steels. For good adhesion, surface cleanliness, proper dip coating, and anti-wear parameters are important; the coating also improves appearance, chemical resistance, and corrosion protection. However, coating choice depends on tool geometry, workpiece material, and cooling conditions; in some cases, the coating can affect conductivity or brittleness, so a careful design analysis is required during the planning phase. As illustrated in Figure 8, the samples of coatings applied to tungsten carbide cutting tools and microstructure.

Figure 8

Samples of coatings applied to tungsten carbide cutting tools and microstructure (Sandvik Coromant, 2025)



Chemical Vapor Deposition (CVD) Coating

The Chemical Vapor Deposition (CVD) was initially conceived as a pioneering manufacturing process, with the objective of producing a range of engineering products, including nanocomposite ceramic coatings and critical components within multiple industrial domains, such as the semiconductor industry, the ceramic industry and the mining industry. In recent times, the scope of the CVD technique has expanded significantly beyond its original parameters, particularly within the domains of semiconductor and microelectronics industries, as a consequence of extensive research activities across a range of disciplines. The reasons for the uniqueness of the chemical vapor deposition (CVD) technique are manifold. These include the ability to produce highly versatile layers, the possibility of applying nanocomposite ceramic coatings to metals, the ease of semiconductor fabrication, and the opportunity to fabricate layers with organic and inorganic substances. The layers that are produced by the CVD technique are typically crystalline or amorphous in nature. These layers possess a range of properties that can be tailored by means of controlling the production parameters. Indeed, the CVD technique is but one of several ceramic coating deposition techniques that have undergone rapid development in recent years. As is widely accepted within the relevant scholarly community, the CVD process results in the creation of a solid layer on the substrate. This phenomenon can be attributed to a chemical reaction occurring within the vapor phase. As is apparent from the evidence presented, the formation of soot, a by-product of incomplete combustion, has been a persistent phenomenon throughout history. This occurrence has been identified in the context of the CVD technique, thereby indicating a possible correlation between the two processes (Sabzi et al., 2023).

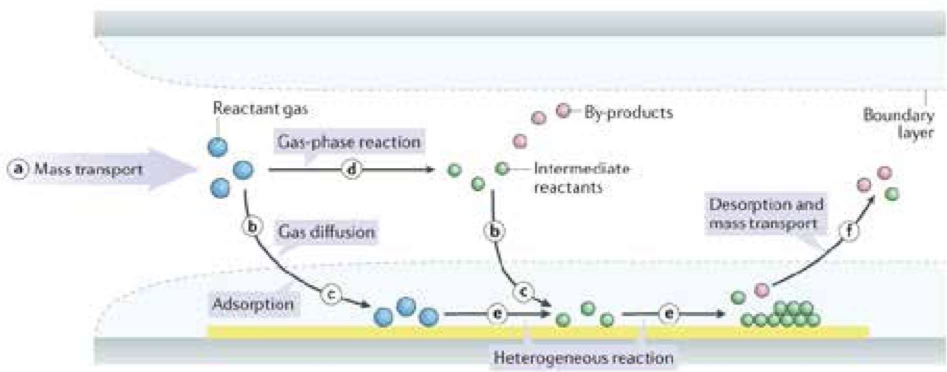
The significance of CVD can be ascribed to the broad spectrum of elements and compounds that can be deposited by this method. It has been determined that such deposits may be formed at comparatively lower temperatures and at ambient atmospheric pressure. The process of depositing films with a high degree of purity is applicable to the following types of films: amorphous, epitaxial, polycrystalline and uniaxially oriented polycrystalline films. CVD includes the chemicals that react, how they react, and how heat and movement work in the reactors. It also includes how materials and energy move in and out of the reactors (Frey, 2015). One of the major benefits of CVD is the capacity to create pure, high melting-point substances at fairly low temperatures. A further benefit of CVD is its considerable throwing power, which facilitates the coating of hidden surfaces, provided diffusion or convection can transport reactants to the area in question. CVD has also been shown to achieve high material deposition rates of tens of micrometers per hour or more (Weimer, 1997).

In contradistinction to physical vapor deposition techniques, like evaporation and sputtering, the chemical vapor deposition confers a distinct advantage by virtue of its reliance on chemical reactions that facilitate the modulation of deposition rates, in addition to the fabrication of products of exceptional quality with unparalleled conformality. CVD facilitates the calibration of the configurations and characteristics of the ensuing artefacts, and a plethora of sophisticated CVD systems and their derivatives have been cultivated, such as plasma-enhanced CVD and MOCVD (metal organic CVD). The requirement of high-vacuum working environments is not a feature of CVD, a factor that leads to its popularity in electronics, surface modification, optoelectronics, and biomedical applications (Sun et al., 2021).

Notwithstanding the variations observed among different CVD types, the fundamental process remains similar in essence and consists of the following common elementary steps (Figure 9). Initially, the reactant gases are conveyed into the reactor. Subsequently, it has been demonstrated that these reactant gases undergo gas-phase reactions to form intermediate reactants and gaseous by-products via homogeneous reactions. Alternatively, they diffuse directly through the substrate's boundary layer. Adsorption and diffusion of reactant gases and intermediate reactants onto and along the substrate's surface is clear. Subsequently, heterogeneous reaction phenomena occurred at the interface where the gaseous state and solid phase met. These reactions led to continuous thin film formation via three processes: nucleation, growth, and coalescence. These were also the processes through which reaction by-products were formed. As a consequence, the desorption of gaseous byproducts and unreacted reactants from the surface of a reaction zone is a well-documented occurrence. It is crucial to recognize that the occurrence of gas-phase reactions is contingent upon elevated temperatures or the introduction of additional energy, such as that which is inherent in the form of plasma. Moreover, in scenarios where the deposition process is contingent on surface catalysis of the underlying substrate, it is crucial to acknowledge the inherent heterogeneity of the reaction. This principle may be illustrated by the process of catalytic growth of graphene on a metal surface (Sun et al., 2021).

Figure 9

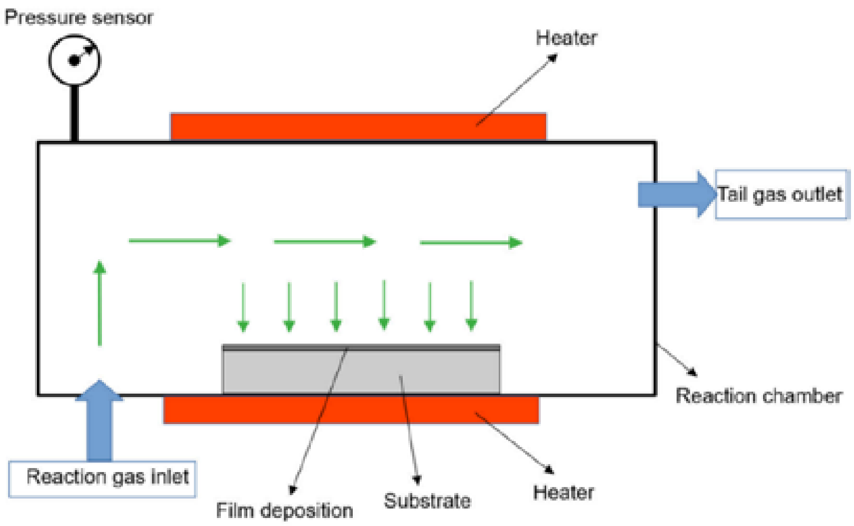
Schematic of general fundamental steps of a typical CVD process (Sun et al., 2021)



Firstly, reactant gases, indicated by blue circles in the schematic representation, undergo transportation to the reactor, which is step a in the process. It is evident that two possible routes are delineated for the reactant gases. Firstly, direct diffusion through the boundary layer is a possibility (step b). Secondly, adsorption onto the substrate is an alternative (step c). Another hypothesis to be considered is that intermediate reactants (green symbols) and by-products (red symbols) could be formed through gas-phase reactions (step d). The subsequent deposition of the reactants and by-products onto the substrate is facilitated by two mechanisms: diffusion (step b) and adsorption (step c). The process of surface diffusion (step e) and heterogeneous reactions are both initiated on the substrate surface. Evidence suggests that these reactions take place prior to the formation of thin films or coatings. In conclusion, the process of desorption of by-products and unreacted species is initiated from the surface, and the subsequent forced extraction of these elements as exhausts is executed (step f). CVD, chemical vapor deposition (Sun et al., 2021). As depicted in Figure 10, the CVD coating process is schematically represented.

Figure 10

Chemical vapor deposition coating method (Ramezani et al., 2023)



In order to satisfy the mounting demands of contemporary technologies, a range of specialized CVD techniques have been devised. These techniques have been customized for specific applications (Heydari Gharahcheshmeh, 2025).

CVD categories and variants

A. Horizontal CVD and vertical CVD are both based on the configuration of the reactor or the direction of gas movement. The horizontal tube reactor represents the most prevalent configuration, wherein the substrates are mounted in a horizontal, vertical, or tilted orientation, with the objective of adjusting the gas movement. The vertical reactor is typically equipped with a showerhead mixer, a configuration that is advantageous for ensuring material uniformity and enhancing the growth rate (Sun et al., 2021).

B. Atmospheric pressure CVD and low-pressure CVD are dependent on the working pressure. In circumstances pertaining to low-pressure CVD, the utilization of a vacuum pump is imperative to ensure the effective regulation of gas flow. By way of contrast, atmospheric pressure chemical vapor deposition does not generally require the utilization of a pump and typically engenders a slow flow rate for the reactive gas. (Sun et al., 2021).

C. The terms “hot-wall CVD” and “cold-wall CVD” refer to the heating methods employed in thermal CVD. In the context of hot-wall CVD, the reaction chamber is subject to the application of thermal energy from an external furnace, ensuring the maintenance of a consistent and uniform temperature throughout the chamber. In the procedure of cold-wall CVD, the substrate and the substrate’s immediate vicinity are the only components that are heated. It is imperative to note that the reactor wall is maintained at a low temperature, thereby facilitating expeditious cycles of heating and cooling. In the field of cold-wall CVD, the employment of resistance heating, hot plates and induction heating methods has emerged as a predominant approach (Sun et al., 2021).

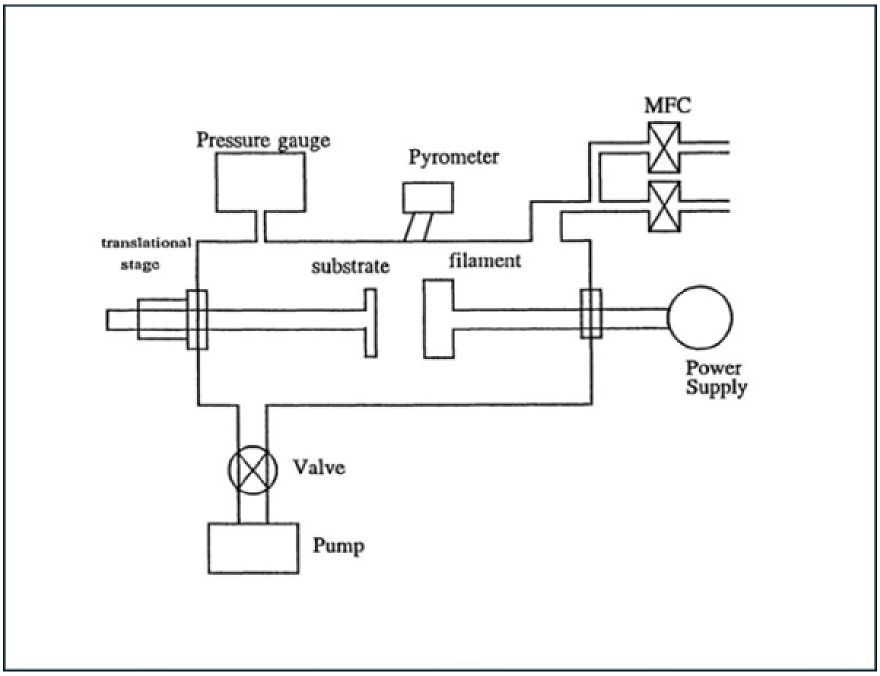
D. It is evident that photo-assisted CVD, plasma-enhanced CVD, and laser-assisted CVD are distinct variations on the theme of thermal CVD. These variants involve the incorporation of supplementary components and the utilization of alternative forms of energy to facilitate the CVD reaction. In the process denoted as plasma-enhanced chemical vapor deposition, plasma is defined as being a partially ionized high-energy gas. This plasma is produced by direct current, radio-frequency voltage or microwave sources and is subsequently coupled to the reactor, thereby leading to a significant decrease in the reaction temperature. In the process of photo-assisted/laser-assisted Chemical Vapor Deposition (CVD), light from either a high-intensity lamp or a laser is utilized with the objective of promoting the desired deposition (Sun et al., 2021).

E. Metal organic chemical vapor deposition (MOCVD) is described as the process of utilizing metal-organic precursors, which are generally volatile liquids, in a controlled manner. These precursors vaporized to form thin films. The MOCVD (Molecular-Beam Epitaxy) technique represents a pivotal method in the fabrication of III-V compound semiconductors and high-temperature super fluids, along with epitaxial layers. The significance of this technique is paramount in the context of manufacturing advancements in electronic and optoelectronic devices (Heydari Gharahcheshmeh, 2025).

F. Hot filament CVD chamber is fabricated from stainless steel and incorporates a tungsten wire filament. The filament is arranged in a vertical orientation. The lower terminal is attached to a braided copper wire, whilst the upper terminal is firmly fixed in position. It is imperative that a stainless-steel substrate holder is utilized in order to facilitate the execution of thin-film deposition. The temperatures of the filament are generally measured at a range of between 2000°C and 2200°C, with filament currents ranging from 50 A to 60 A. The substrate temperature is generally determined within the 950 °C–1,000 °C range during the course of CVD diamond thin film deposition. The feed gases consist of 99.999% hydrogen and 99.8% methane. The pressure within the chamber is meticulously regulated within the 30-100 Torr range. The schematic representation of the hot-filament CVD process is depicted in Figure 11 (Manawi et al., 2018).

Figure 11

Schematic representation of the hot-filament CVD chamber (Manawi et al., 2018)



G. Initiated CVD (iCVD) technique entails the utilization of vapor-phase reactants, encompassing an initiator and monomers. These reactants undergo a process of chain-growth polymerization subsequent to their adsorption onto a substrate that has been subjected to temperature control. The utilization of an initiator enables the attainment of considerably lower filament temperatures, thereby ensuring the preservation of the monomer's organic functional groups. The retention of functional groups enables precise control over the wettability and surface reactions of the film. Meanwhile, iCVD has been evidenced to facilitate the deposition of polymer films which exhibit controlled thickness and composition. This has resulted in an expanded use of CVD, encompassing surface coatings, biomedical applications, and nanostructured materials (Heydari Gharahcheshmeh, 2025).

H. Oxidation chemical vapor deposition (oCVD) process is a one-step approach that directly converts vapor-phase monomers and oxidant vapors into thin conjugated, conducting and semiconducting polymer films. It is at the substrate surface that a combination of step-growth polymerization and simultaneous doping occur within a single deposition step. Precise control of the properties of oCVD-derived thin films is achievable through meticulous adjustments to the flow rates of the reactants in the vapor phase. This process involves the modulation of other crucial parameters such as the deposition temperature and chamber pressure. The oxidant saturation ratio (OSR) in the oCVD method is a critical process parameter with significant implications for the texture and nanostructure of the deposited thin films, and thereby the electrical conductivity of the resultant material. In the event of multiple monomers being introduced, the flow rate ratios of these monomers can be modified to allow for the precise calibration of the composition and characteristics of the ensuing copolymer films. One of the most advantageous features of oCVD is its versatility as a deposition technique. Some of the benefits of oCVD include the ability to form conformal coatings, process at low temperatures, and carry out solvent-free synthesis. Other advantages include the capacity for uniform film growth, mechanical flexibility, scalability for industrial applications, and substrate independence (Heydari Gharahcheshmeh, 2025).

oCVD is a process that is contingent upon the spontaneous reaction between oxidant gases and monomer vapors upon their adsorption to the substrate, thereby producing step-growth polymerization, which, by and large, results in the formation of conducting or semiconducting polymer films. The process of organic chemical vapor deposition (oCVD) has been established as a facilitating factor in the fabrication of conjugated, conducting and semiconducting polymers. This development presents novel opportunities for the realization of flexible electronics and organic optoelectronics (Heydari Gharahcheshmeh, 2025).

I. Molecular layer deposition and atomic layer deposition are two similar variants of CVD for the deposition of inorganic and organic thin films correspondingly. The process of molecular and atomic layer deposition involves the introduction of precursors sequentially. The deposition of high-quality thin films by the layer-by-layer method is known to be characterized by self-limiting absorption and surface reactions of the precursors. Subsequent to the deposition of each stratum, the residual precursor is eradicated by the carrier gas (Sun et al., 2021).

Sol-Gel Coating

Sol–gel protective coatings have exhibited remarkable properties with regard to chemical stability, oxidation control, and improved corrosion resistance for metal substrates. Furthermore, the sol–gel method constitutes an ecologically sustainable technique of surface protection. It has been evidenced that the substance under consideration has the capacity to substitute for the noxious pretreatments and coatings that have traditionally been employed to enhance the corrosion resistance of metals (Wang & Bierwagen, 2009). It has been evidenced that the sol-gel method is a highly effective process for the production of adherent and chemically inert oxide or hybrid films. These films can be produced at relatively low temperatures (Hegde et al., 2024).

A plethora of techniques can be utilized to facilitate the process of applying coatings to metallic surfaces. A number of processes are worthy of note, including electrochemical deposition, PVD, CVD, plasma spraying and sol–gel processes. The utilization of sol–gel coatings is beneficial for a number of reasons. The following list enumerates several of the most significant features (Wang & Bierwagen, 2009):

- The temperature at which sol–gel processing is generally conducted is low, frequently approximating room temperature. It is therefore evident that the process of thermal volatilization and degradation of entrapped species, such as organic inhibitors, is minimized (Wang & Bierwagen, 2009).
- The utilization of liquid precursors in the casting process enables the fabrication of coatings with intricate geometries and the production of thin films, obviating the necessity for conventional machining or melting techniques (Wang & Bierwagen, 2009).
- The formation of sol–gel films is achieved through the utilization of "green" coating technologies: The method is distinguished by its utilization of compounds, a process which prevents the introduction of impurities into the end product during the preliminary phase of the procedure. This approach is notable for its waste-free nature and the elimination of the washing stage, which are major benefits in terms of efficiency and environmental impact (Wang & Bierwagen, 2009).

Preparation of sol–gel coatings

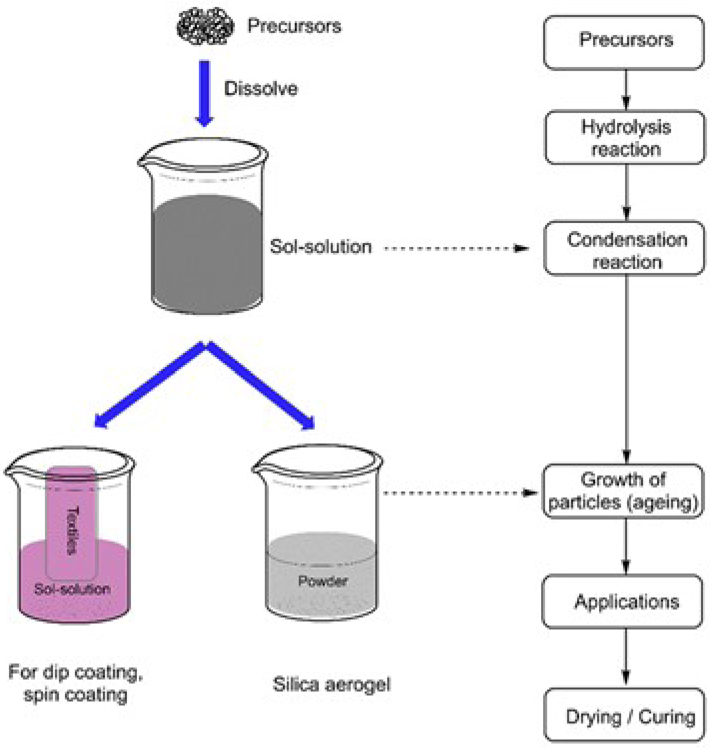
The sol-gel process may thus be delineated as a sequence of reactions between molecular precursors in a liquid medium, which results in the formulation of an oxide network. In summary, there are two fundamental methodologies that are utilized in the fabrication of sol-gel coatings. The two methodologies are the inorganic and the organic methods. The inorganic method is distinguished by the development of networks via the establishment of a colloidal suspension (typically oxides) and the subsequent gelation of the sol (a colloidal suspension of particles measuring between 1 and 100 nanometers) to form a network within a continuous liquid phase. Nevertheless, it is imperative to acknowledge that the most widely utilized methodology is the organic approach, which is typically commenced with a mixture of monomeric metal or metalloid alkoxide precursors $M(OR)_n$ in an alcohol or other low-molecular weight organic solvent (Wang & Bierwagen, 2009).

Sol-gel is a wet processing method in which a homogenous precursor solution is formed by dissolving the raw material in a solvent, whether this is water or an organic solvent.

This step, irrespective of whether the precursor material consists of an inorganic salt or a metal alkoxide, is the foremost stage in the sol-gel procedure. Sol-gel processes are categorized into five distinct stages: firstly, hydrolysis, followed by condensation (gelation), then gel aging, then the application stage and finally the curing stage (Periyasamy et al., 2020). The sol-gel process is depicted schematically in Figure 12.

Figure 12

Steps constituting a sol-gel process (Periyasamy et al., 2020)



In the majority of instances, the dissolution of inorganic or metal-organic precursor substances is carried out in an alcohol-based solvent. Subsequently, a hydrolysis process is initiated, involving the application of water and a condensation reaction. This process results in the formation of dispersed fine particles or polymers, which are collectively referred to as sol. In summary, the process of forming interconnections between sols leads to the establishment of an inorganic polymer network, which is widely recognized as ‘gel’. This network contains remnants of water and solvents. It is broadly acknowledged within the scientific community that the process of formation or coating occurs during the transition period from solution to gel. This procedure is conducted prior to the removal of the residual water and solvents, and results in the formation of a dry gel. Subsequent application of heat to the gel has been demonstrated to facilitate the process of dense final product formation (Tan et al., 2021).

Irrespective of the technique used, a substantial contraction in volume and internal stress accumulation occur after deposition. This is due to substantial evaporation of solvents and water. Cracks are prone to formation due to internal stress if the conditions for film formation are not met with the requisite degree of rigor. It is apparent that the process of curing and the subsequent heat treatment of sol–gel coatings exhibit significant variability. This variability is contingent on the presence of disparate microstructures, stringent quality requirements, and the practical applications concerned (Wang & Bierwagen, 2009). The sol–gel solution is employed in conjunction with coating techniques, including dip, spray, and spin coating. The utilization of sol–gel technology in conjunction with a substrate engenders the establishment of a robust and substantial surface that subsequently overcomes the irregularities present after being subjected to a precise temperature (Zanurin et al., 2022).

Ceramics are considered to be effective coating materials due to their favorable thermal and electrical properties, in addition to their resistance to corrosion, wear and oxidation. The process of synthesizing ceramic coating using the sol–gel method has been evidenced to exhibit several advantageous features. These include relatively low cost and simple methodology. The implementation of the sol–gel method facilitates the coating of complex geometries, with the thickness of the coating being readily adaptable for a range of applications. Ceramic coating can be categorized into two distinct classifications: oxides and non-oxides. Oxide ceramics are non-metallic and naturally inorganic compounds, including alumina, zirconia, silica and magnesia. The oxide ceramic coating exhibited favorable electrical properties, minimal wear resistance, and excellent oxidation resistance. It is evident that the non-oxide ceramic does not exhibit greater or lesser oxide properties. The most notable properties are thermal shock resistance and resilience against fractures. Typical oxides comprise alumina and zirconia, whilst non-oxides principally consist of carbides, borides, nitrides and silicides (Zanurin et al., 2022).

The necessity of regulating the interactions between materials and their immediate environment is contingent on the material's surface characteristics. In light of this, the sol-gel process is being utilized with increasing frequency in the modification of the surfaces of a variety of materials, including metals, organic polymers, inorganic particulates, and glasses. This method allows for control of properties such as wettability, biocompatibility, porosity, corrosion, catalytic activity, and the selective adsorption of analytes, at the level required by the substrate surfaces to which these properties are applied. Consequentially, the utilization of sol-gels has garnered interest within diverse scientific and technological domains, such as metallurgy, biomaterials, analytical chemistry, and photocatalysts. A salient feature of the technique is its economic viability, making it a suitable option for large-scale applications (Carrera-Figueiras et al., 2019).

Notwithstanding, the methodology of sol-gel synthesis is distinguished by its remarkable versatility, which has engendered the fabrication of a wide variety of materials. The utilization of these materials has been observed within diverse scientific and technological domains. The versatility of sol-gel techniques has given rise to a substantial degree of interest in their application to the field of coating development. The utilization of these coatings in analytical chemistry is driven by the objective of enhancing the efficiency and specificity of sorbents. This enhancement process serves to facilitate the concentration of desired analytes, thereby ensuring the effective analysis of chemical substances. In the domain of biomedical engineering, sol-gel coatings have garnered attention for their potential in regulating the surface interactions between medical implants and devices and biological environments. In the domain of photocatalysis, sol-gel coatings have been developed for applications such as organic compound degradation. The application of anticorrosion sol-gel coatings is a material management strategy that aims to mitigate the degradation of materials and metallic structures. This approach is employed to preserve the surface and bulk integrity of metallic materials, thereby ensuring their functionality and longevity. The sol-gel coating technique is a method of coating a substrate in a “sol” solution, followed by the vertical extraction of the substrate at a controlled speed. It is evident that a very fine coating of gel is thus formed, since there is rapid evaporation of the solvent during the extraction of the substrate. The coating’s thickness is determined by the liquid’s viscosity, surface tension, and the rate of removal; it is evident that an accelerated rate of removal will result in a greater thickness of the coating. Subsequent to the acquisition of the initial coating layer, the process can be reiterated to create a multilayer structure. The drying step also exerts influence on the final structure of the film, and thickness limits must be observed in order to prevent cracking or detachment of the film from the substrate (Carrera-Figueiras et al., 2019).

Conclusion

The progressive development of coating technologies is a consequence of the necessity to satisfy the increasing industrial requirements and the high-performance expectations that have been established. A wide range of solutions is offered by thermal spraying, PVD, CVD and sol-gel methods. The advantages of these methods are dependent on several factors, including the type of material, the application area and the cost requirements. The application of thermal spraying is particularly prominent in cases requiring high wear resistance; meanwhile, both PVD and CVD methods are preferred for the creation of both thin and high-purity coatings, as well as for controlled coatings. Conversely, sol-gel offers a viable alternative for functional coatings, attributable to its effectiveness at low temperatures and its capacity for versatility. In the future, the integration of nanotechnology with hybrid coating technologies and environmentally friendly processes is predicted to lead to substantial improvements in the performance of these methodologies. It is to be anticipated that this will pave the way for the advancement of more innovative and sustainable applications. Consequently, the utilization of advanced coating technologies is poised to not only address prevailing industrial challenges but also remains a pivotal element in the design of future generations of products.

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Artificial Intelligence-Based Automation and Robotic Technologies

Hasibe Nur KILINC
Necmettin Erbakan University

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Introduction

This study offers a thorough overview of robotics and artificial intelligence, emphasizing the development of robotic systems and core AI concepts, including machine learning, natural language processing, decision making, computer vision, and automated planning. It also examines the architecture and benefits of automation in robotics, providing definitions of automation systems, categorizing levels of automation, and exploring the technical and operational challenges encountered during their implementation. Furthermore, recent advancements in AI enabled autonomous robots across various domains such as autonomous vehicles, medical robots, industrial automation, humanoid robots, and agricultural robots are discussed (Rayhan, 2023).

Artificial intelligence has significantly transformed both professional environments and everyday life. Autonomous systems are anticipated to assume a central role across diverse domains, including maritime operations, space exploration, aviation, field robotics, terrestrial robotics, and service robotics. These systems not only perform repetitive and routine tasks but also enhance workforce productivity and overall operational quality. The integration of robotics and AI is facilitating the creation of intelligent computational systems with capabilities such as situational awareness, responsiveness, and cognitive reasoning. In addition, robotic process automation (RPA) streamlines workflows, improving efficiency and enabling more effective task execution across multiple industries (Khan, Chowdhury & Nandy, 2023).

AI driven technologies have become highly transformative, reshaping numerous sectors across the economy. The significance of artificial intelligence and robotic systems increased notably during the Fourth Industrial Revolution and the emergence of Industry 4.0, first introduced at the Hannover Fair in Germany in 2011. During this period, primary objectives centered on reducing reliance on human labor while developing autonomous systems capable of executing complex tasks with high efficiency (Cuhadar, Demiray, et al., 2022).

The adoption of AI and robotic technologies continues to expand in both social and economic contexts, influencing areas ranging from public services to daily human activities. Within this framework, the tourism and hospitality sectors have rapidly embraced technological innovation. Emerging technologies including robotics, virtual and augmented reality, artificial intelligence, IoT, blockchain, autonomous vehicles, nanotechnology, quantum computing, and 5G are transforming customer experiences while reshaping management and marketing strategies across service industries (Cuhadar, Demiray, et al., 2022).

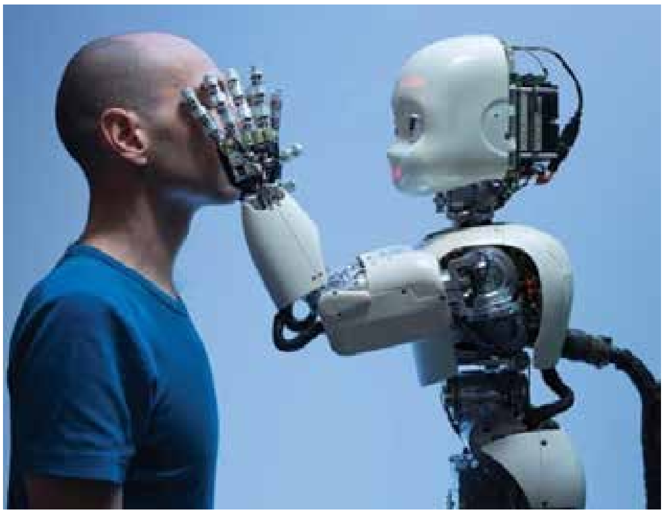
AI and robotic applications are increasingly utilized in tourism sub sectors such as travel, transportation, food and beverage, and accommodation, enhancing operational efficiency and enriching customer experiences. In hospitality, service robots autonomous AI systems capable of detecting and responding to guest needs are actively deployed in areas such as front office operations, room service, and housekeeping, thereby improving service quality and performance (Cuhadar, Demiray, et al., 2022).

Robotics and automation play a central role in enhancing efficiency within industrial production processes and significantly influence enterprise competitiveness. The adoption of advanced automation technologies including integrated assembly systems, industrial robots, and image processing solutions supports both cost reduction and the achievement of high quality production standards. This trend is especially evident in developing countries, where strategies are being adopted to enable technology transfer from advanced economies, support licensed production models, and attract high tech investments through collaborative R&D initiatives. In this context, robotic technologies function as essential drivers of industrial development and economic growth.

Automation is a fundamental driver of efficiency and quality across diverse operational domains. A key advantage of automation is its ability to deliver precise and consistent repetition, which is often difficult or impossible to achieve through manual labor. Beyond this, automation supports quality enhancement at multiple stages of manufacturing and process management. In recent years, rapid advancements in information technologies particularly those driven by artificial intelligence and robotics have profoundly reshaped industrial operations and global business practices. Consequently, many countries have implemented national strategies and dedicated programs to foster innovation and advance the development of AI and robotic technologies.

Figure 1

Artificial Intelligence Robotics Technology (Khan, Chowdhury & Nandy, 2023).



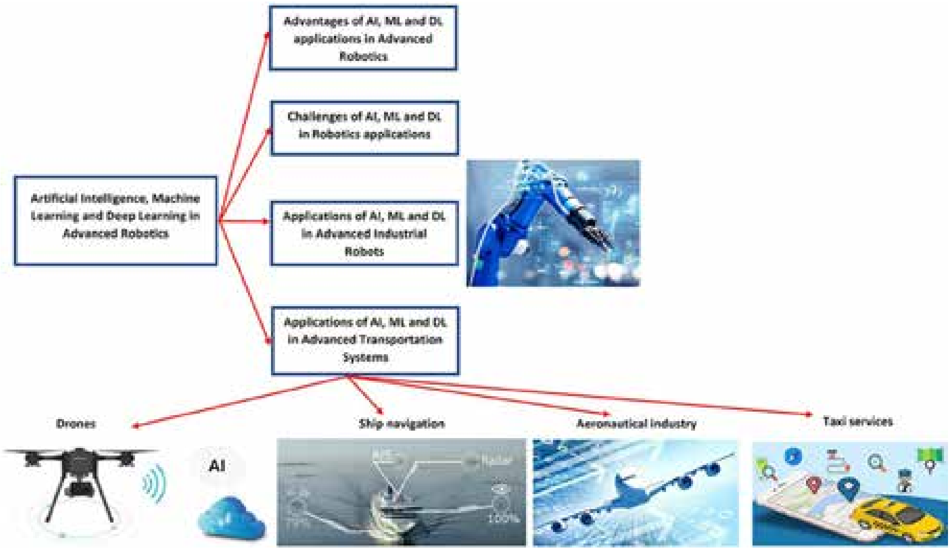
The advent of the IoT has enabled the transformation of traditional physical objects into intelligent devices capable of connecting and communicating over the Internet. These interconnected devices can seamlessly exchange data and interact within complex digital ecosystems. Such technological developments have also prompted important ethical considerations concerning the potential responsibilities and decision making roles that artificial intelligence and robotic systems may assume in relation to humans.

The integration of AI into robotic systems primarily aims to enhance the practicality, flexibility, and efficiency of industrial robots. Nevertheless, certain specialized domains such as collaborative robotics and autonomous mobile robots, remain in the early stages of technological maturity and have yet to fully realize their potential capabilities.

With the continuous integration of artificial intelligence and automation technologies, laboratory automation has emerged as a critical component of this transformation. Automating laboratory workflows accelerates experimental procedures, enhances accuracy by reducing human error, and optimizes resource utilization, ultimately lowering operational costs and shortening the time to market for both scientific and industrial innovations (Zhang, Liu, Chen, et al., 2025).

Figure 2

Artificial Intelligence Robotics Technology (Soori, Arezoo & Dastres, 2023).

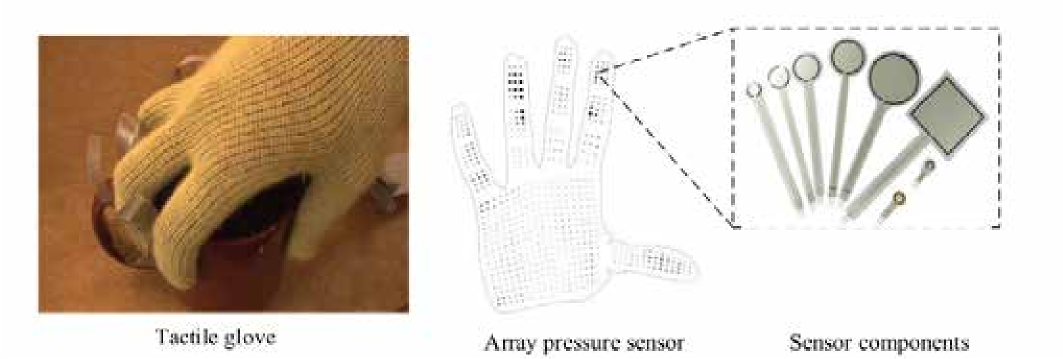


In advanced robotic systems, artificial intelligence serves as a fundamental component enabling robots to perceive their surroundings, reason about complex situations, and operate autonomously within dynamic environments. Machine learning techniques enhance these systems by allowing robots to continuously improve their performance through experiential learning and data driven adaptation. Meanwhile, deep learning is employed to address tasks that are challenging for conventional machine learning approaches, such as image and speech recognition. The integration of these technologies empowers robotic systems to execute sophisticated tasks once considered unattainable. The combined application of artificial intelligence, machine learning, and deep learning in robotics is essential for elucidating the interconnections among these technologies and for advancing the analysis and optimization of robotic systems (Soori, Arezoo & Dastres, 2023). The examples below highlight the wide ranging applications of these technologies across different robotic systems.

1. Object Detection and Recognition: Deep learning techniques have substantially enhanced the capabilities of robotic systems to execute essential including object detection, tasks and recognition. By employing artificial neural networks trained on large, labeled datasets, robots can accurately identify and classify objects within their operational environment, enabling more precise and reliable interactions (Bai, Li, Yang et al., 2020).

Figure 3

Tactile sensor schematic (Bai, Li, Yang et al., 2020).

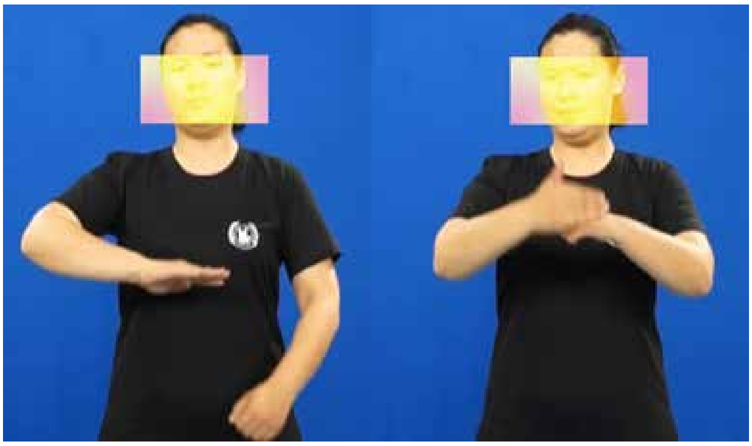


2. Predictive Maintenance: Artificial intelligence and machine learning–driven predictive maintenance systems are developed to identify potential component failures before they occur. By analyzing data from sensors and other sources, these systems can anticipate which robotic components are likely to fail and predict the timing of such events, enabling proactive maintenance measures that minimize downtime and improve operational reliability (Lee, Wu, Yun et al., 2019).

3. Gesture and Speech Recognition: Artificial intelligence enhances robotic systems with capabilities such as gesture and speech recognition, facilitating natural and intuitive human–robot interaction. For instance, social robots like Pepper can interpret human gestures and respond to voice commands, making them applicable in diverse domains including customer service, healthcare, and entertainment (Jiang, Satapathy et al., 2020).

Figure 4

Keyframe expression of a gesture sample: "safety" (Bai, Li, Yang et al., 2020).



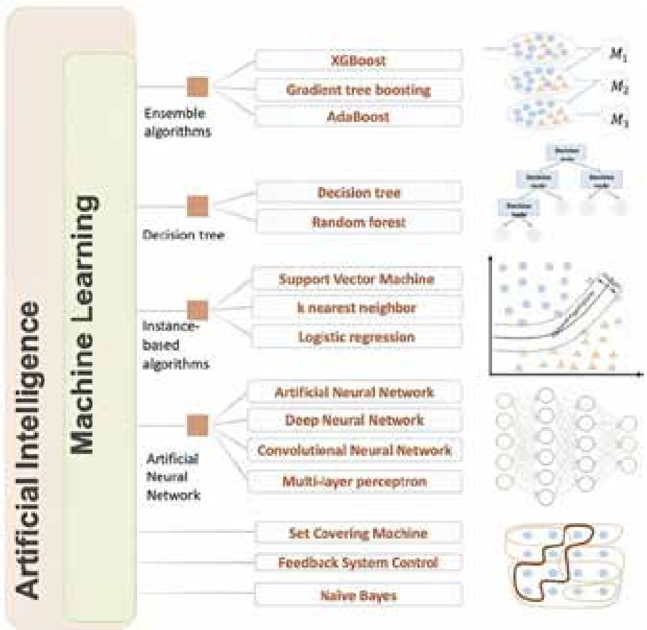
4. Robotic Surgery: Machine learning algorithms and artificial intelligence are instrumental in enhancing both the precision and safety of complex

procedures performed using surgical robotic systems. These systems assist surgeons throughout operations by reducing intraoperative risks and improving postoperative outcomes. In particular, deep learning models provide advanced image analysis and decision support capabilities, enabling more accurate and efficient surgical interventions (Panesar, Cagle et al., 2019).

5. Medical Applications: Beyond robotic surgery, AI and machine learning are increasingly applied across various medical domains to improve clinical decision making and procedural accuracy. Deep learning techniques, in particular, support diagnostic imaging, treatment planning, and patient monitoring, offering enhanced precision, efficiency, and reliability in healthcare delivery (Nguyen & Do, 2019).

Figure 5

Drug delivery using machine learning algorithms is utilized to treat infectious diseases (He, Leanse & Feng, 2021).



Artificial intelligence enables robots to detect objects in their environment, navigate complex environments, and make accurate decisions based on real time data. Machine learning allows robots to learn from previous experiences and adapt quickly to new situations. Deep learning and language processing technologies enable robots to successfully perform multi stage and complex tasks that are difficult with traditional programming methods.

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Experimental Verification of the Process Windows for a Conical Shape Part Manufactured by Hydromechanical Deep Drawing Process

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Introduction

Hydromechanical Deep Drawing Process

The hydroforming process was introduced as a novel method to overcome the limitations of the limiting drawing ratio (LDR) encountered in sheet metal parts manufactured by classical forming techniques. Compared to conventional methods, hydroforming enables the manufacture of more complex and challenging geometries in fewer steps and with higher quality, utilizing fluid pressure as a forming medium. A significant advantage of this process is its potential to reduce die costs by up to 90%.

Hydromechanical Deep Drawing (HMDD) is an advanced manufacturing technique and a type of hydroforming process that differs from the classical deep drawing process by utilizing high-pressure fluid instead of a female die. In this method, the punch moves the sheet metal blank controllably into the high-pressure fluid, which forms the material. The blank holder secures the sheet against the die, controlling material flow and ensuring sealing during the process. As the punch advances into the fluid, the fluid pressure increases. This enhances the friction force between the punch and the sheet material, thereby preventing localized thinning. Despite its benefits, the widespread adoption of HMDD is limited by two main challenges: the difficulty in determining the optimal fluid pressure and blank holder force loading profiles, and the complexity of controlling these profiles accurately on the press.

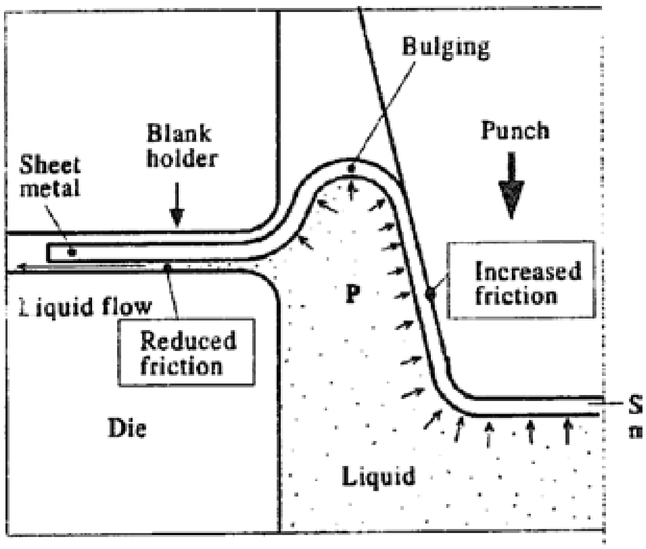
The foundational development of hydroforming technology is credited to Japanese researcher Y. Kasuga, who initiated detailed research and development in 1955. His work culminated in the period from 1958 to 1964 with the introduction of "pressure-lubricated deep drawing." Following this, in the 1970s, K. Nakamura and T. Nakagawa advanced the field further by working on the "hydraulic counter-pressure fluid forming process."

Their continued research led to the development of the "radial-pressure deep drawing method" to facilitate the production of deeper parts, as documented by Nakamura et al. (1987).

In their 2011 study, Halkacı et al. demonstrated that the success of the HMDD process is highly dependent on parameters such as fluid pressure (P), blank holder force (BHF), pre-bulging height, sheet thickness, and friction. They highlighted the critical interaction between fluid pressure and blank holder force, noting that excessively high values of both P and BHF lead to sheet tearing, while insufficient values result in wrinkling. Corroborating this, Akay (2014) also emphasized the necessity of determining the optimal P and BHF for successful part formation. A summary of these effects occurring during HMDD is illustrated in Figure 1.

Figure 1

Effects in HMDD (Nakagava et al., 1997)



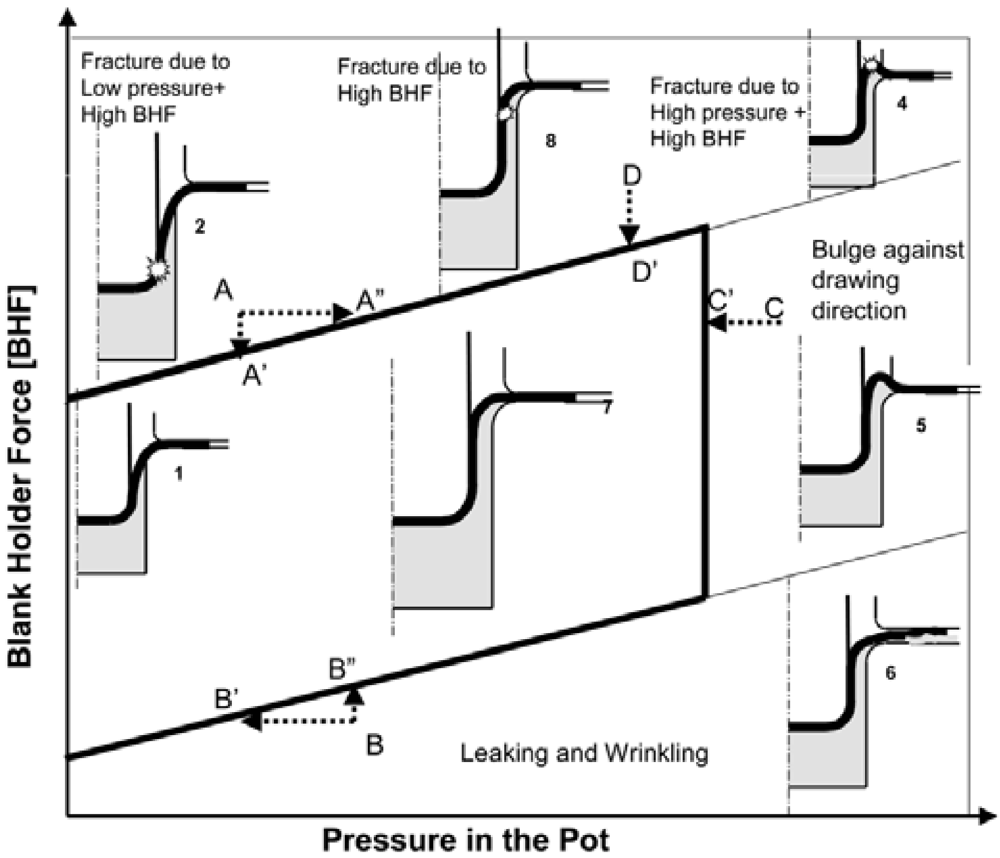
Process Window

Process Windows (PWs) are graphical representations that define the acceptable ranges of key parameters in manufacturing processes. Typically depicted in diagrams that vary at least two critical parameters, they identify a central region of feasible operation, bounded by limits where the process fails, such as by tearing or wrinkling in forming operations. These windows are specific to a part's material and geometry, serving as essential guides for successful production. The concept of process windows is well-established in various manufacturing technologies, including hot forging, ring rolling, friction stir welding, and hydroforming. In HMDD, the use of process windows is crucial. Achieving successful part manufacturing is directly dependent on determining the optimal loading profiles for fluid pressure and blank holder force, which a well-defined process window effectively provides.

A process window is typically divided into four distinct regions: a safe zone, tearing, wrinkling, and leakage. In the preparatory phase, parameters such as sheet metal thickness, part geometry, the limiting drawing ratio (LDR), and the punch and die radii are predetermined. When constructing the process window, the punch velocity and fluid pressure are the primary variables utilized, as these can be actively controlled to define the optimal forming limits. A representative HMDD process window, established based on these relationships, is presented in Figure 2.

Figure 2

Process window in a HMDD Process (Braedel et al., 2005)



The purpose of the process window is to show at which parameters successful results can be obtained, to express it graphically in an understandable way, and to perform the process along the desired line towards the wrinkling-tearing region in a minimum or maximum manner.

1. The process window or process maps can be obtained with multiple analyses, provided that they are experimentally verified.
2. For the parameter optimization of a new process, a process window must be established to determine the constraints that need to be known.
3. In the stage following the obtaining of the process window, obtaining the optimum loading curve becomes a complementary and important study.
4. Especially if, by the nature of the process, at least one parameter changes

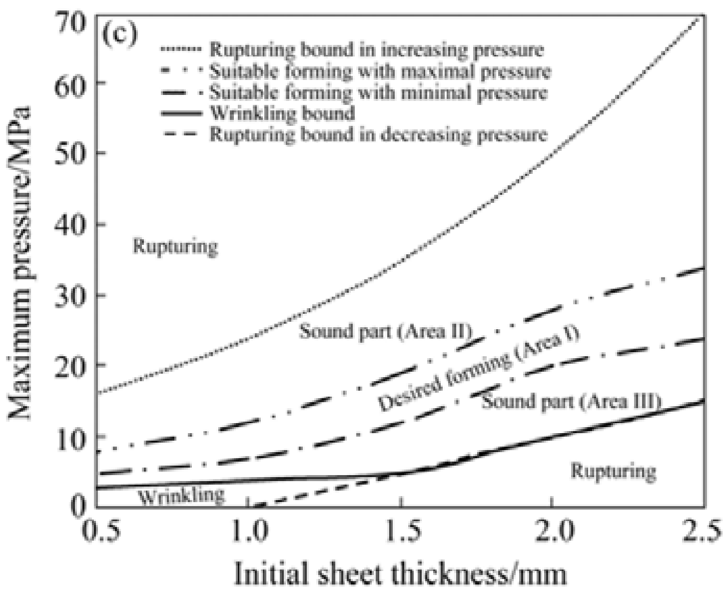
throughout the process, an optimum loading profile that provides suitable forming must be found.

In hydroforming, the process window depends on friction, the geometry of the part to be manufactured, the mechanical properties of the sheet metal, fluid pressure, and the blank holder force.

In their 2015 study, Hashemi et al. developed Process Window Diagrams (PWDs) for aluminum, copper, and steel materials in radial pressure-assisted hydrodynamic deep drawing. The PWD of the steel was shown in Figure 2.8. These diagrams enable rapid assessment of sheet metal manufacturability while reducing the need for extensive experimental work through finite element analysis. For steel, results demonstrated that lower initial sheet thickness and higher strength correlate with improved formability and more uniform thickness distribution. The PWD successfully predicts the feasible forming zone and potential failure modes under various loading conditions (Hashemi et al., 2015).

Figure 3

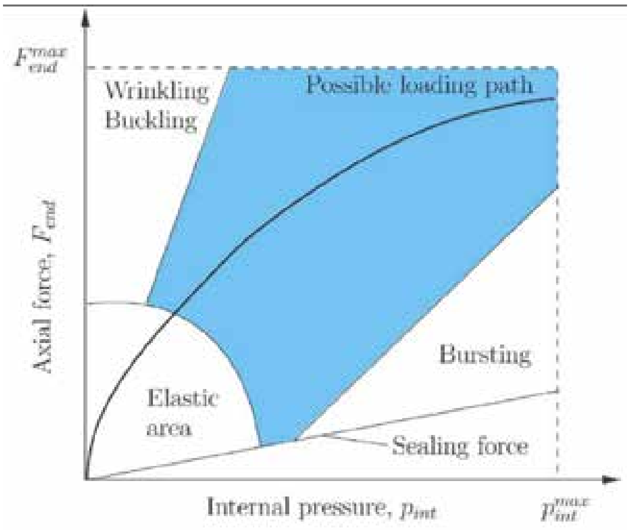
Steel material (St 14) process window (Hashemi et al, 2015).



Aydemir et al. (2005) gave an optimal loading curve for tube hydroforming processes, as illustrated in Figure 4. It is possible to see suitable parameter levels for a successful forming process.

Figure 4

The process window for tube hydroforming (Aydemir et al., 2005).



Sadegh-yazdi et al. (2018) used an adaptive simulation that is integrated with the fuzzy control system with the artificial bee colony (ABC) algorithm to determine the optimized radial and chamber pressure paths in hydrodynamic deep drawing assisted by radial pressure process (Figure 5). They compared the sheet material they had pre-studied with SE analysis to minimize tearing and wrinkling before and after optimization, and they succeeded in obtaining a wrinkle-free product with minimum thinning after optimization (Figure 6).

Figure 5

The hydrodynamic deep drawing assisted by radial pressure process (Sadegh-yazdi et al. 2018).

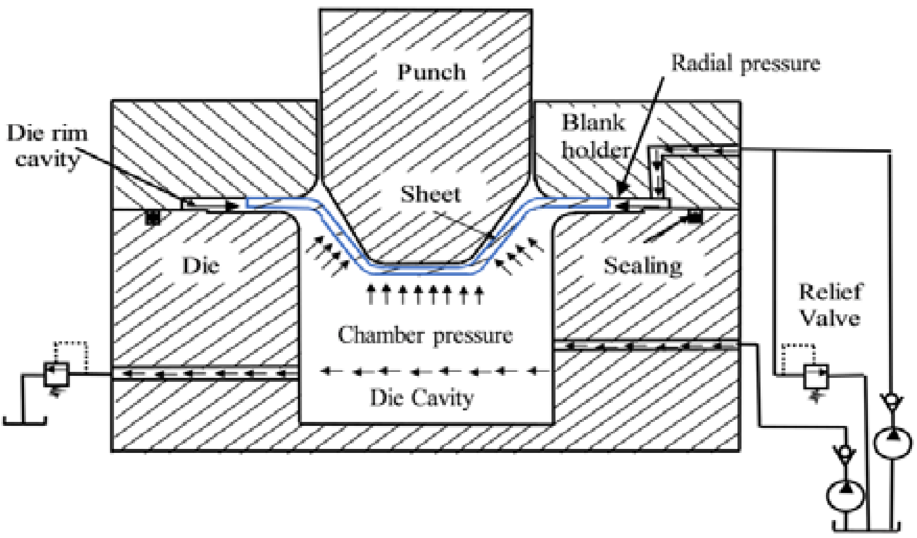
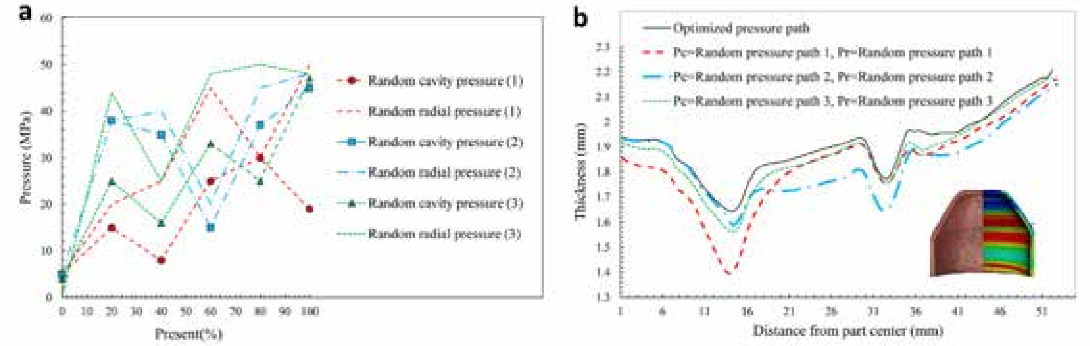


Figure 6

a)Random pressure paths b) Appropriate thickness distribution curve by optimizing the pressure paths (Yazdi et al. 2018)



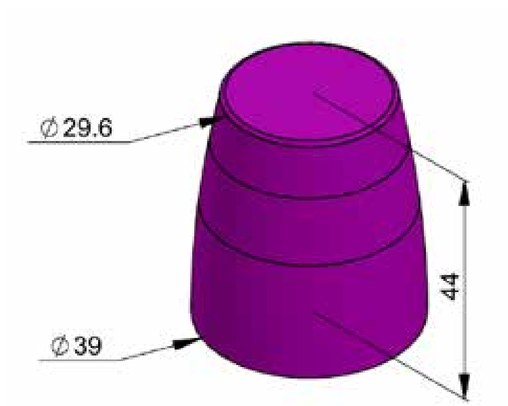
In summary, the literature shows that successful part manufacturing by the hydroforming method predominantly requires the optimization of fluid pressure and blank holder force loading profiles. Process windows have been investigated for various methods, including female die forming, male die forming (HMDD), and tube hydroforming. Previous research on process windows in HMDD has notably not utilized stainless steel and has primarily focused on cylindrical parts. In this study, the process window for a conical shape part from AISI 304 stainless steel was determined experimentally and numerically, and the numerical process window was verified. Consequently, the optimal process parameters will be determined to successfully manufacture the conical part via the HMDD method without sidewall wrinkling.

Determining the Process Window

In this study, separate process windows were determined for liquid pressure and blank holder force (BHF) for a conical shape part (Figure 7) by Finite Element Analysis (FEA) then they were validated by Hydromechanical Deep Drawing (HMDD) experiments. Determination of the process window was explained in a previous study (Özçelik and Türköz, 2019).

Figure 7

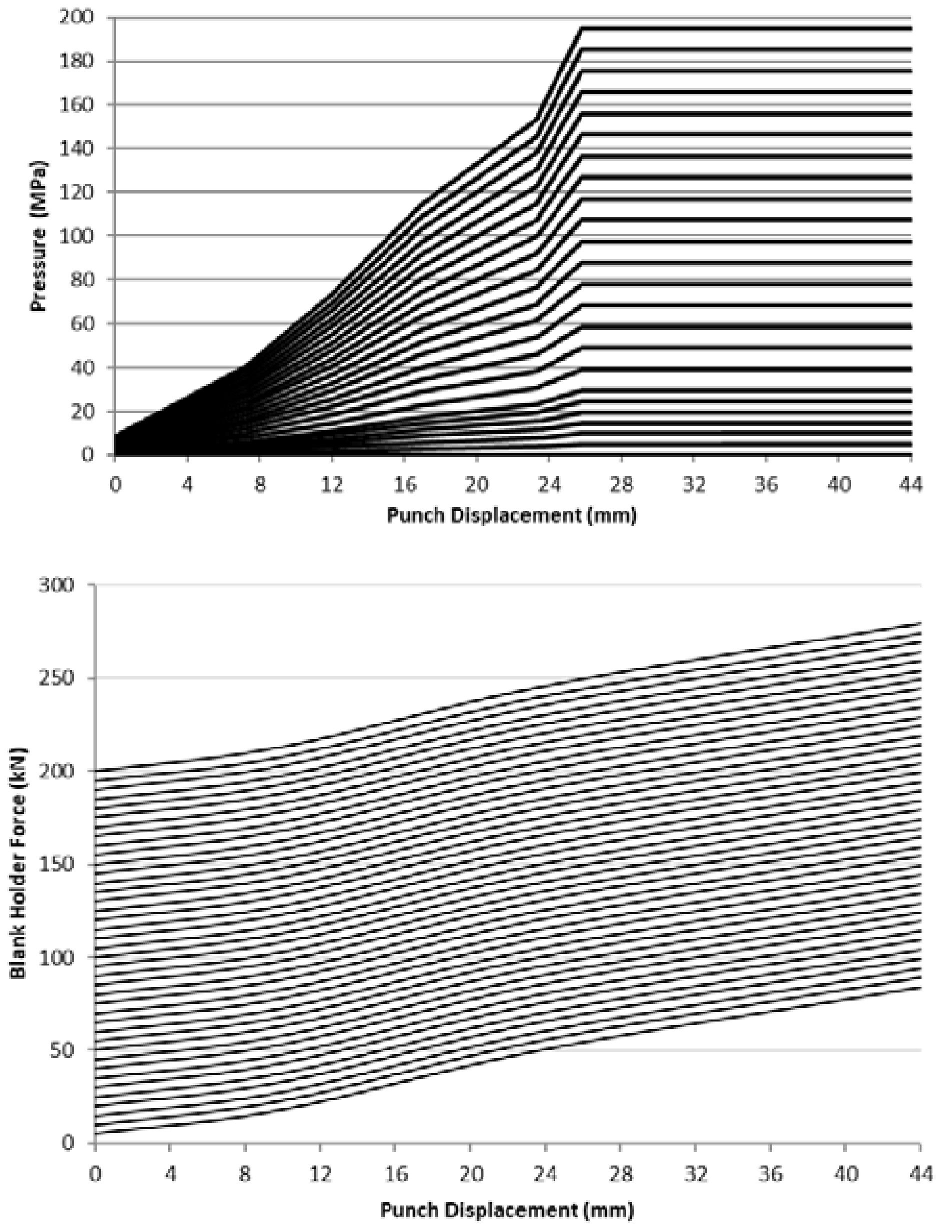
Process window determined canical shape part for HMDD Process



90 analyses were conducted for liquid pressure and 80 for BPK. To determine the liquid pressure process window, constant-pressure, linearly increasing, and increasing curves with different characteristics were tested, and the pressure values at which tear and wrinkling damage occurred, depending on the stamp position, were determined. Constant-pressure curves were applied in 10 MPa increments, starting from 0 MPa to 300 MPa. The linearly increasing and different characteristics liquid pressure and BHF curves are shown in Figure 8. As a result of the analyses, the stamp positions at which tear and wrinkling damage criteria occurred and the corresponding liquid pressure values were determined.

Figure 8

Loading profiles used to create the process window a) For liquid pressure b) For BHF



Experimental Procedure

The process window constructed from the FE analyses was validated by HMDD experiments by using a hydroforming press located in the Hydroforming Laboratory of Konya Technical University. The press has a capacity of 60 tons for both the blank holder and punch forces, and can achieve fluid pressure up to 1600 bar (Figure 9). It was equipped with a Hydraulic Numerical Control (HNC) system, the press enables precise control of the blank holder force, punch position and velocity, and fluid pressure. AISI 304 sheet metal with a thickness of 0.18 mm was used. The sheets were laser-cut to a diameter of 85 mm. To facilitate smooth material flow between the die and blank holder, both sides of the blank were lubricated with paraffin.

Figure 9

The hydroforming press used in the experiments.

For the HMDD experiments, four different fluid pressure profiles and four distinct BHF levels were selected to generate varying forming outcomes within the process window. The actual failure modes observed in the formed parts were compared with the failure modes predicted by the process window, confirming the accuracy of the developed process windows.

Results and Discussion

The stress-strain curves of the AISI 304 material are presented in Figure 10. Using the material's flow curve in Finite Element (FE) analyses of the HMDD process for the conical part, the process windows for pressure and blank holder force were determined, as shown in Figures 11 and 12, respectively. The methodology for conducting the FE analyses is explained in Özçelik and Türköz (2019).

Figure 10

Engineering and true tensile test curves at rolling direction (RD), diagonal direction (DD), and transverse direction (TD)

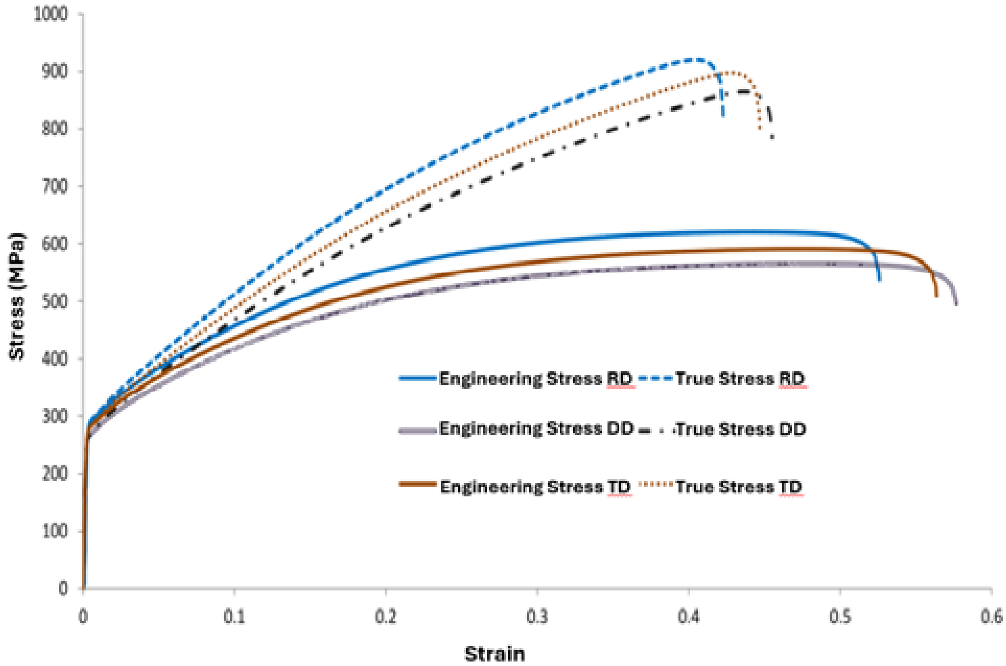


Figure 11

The process window for the fluid pressure

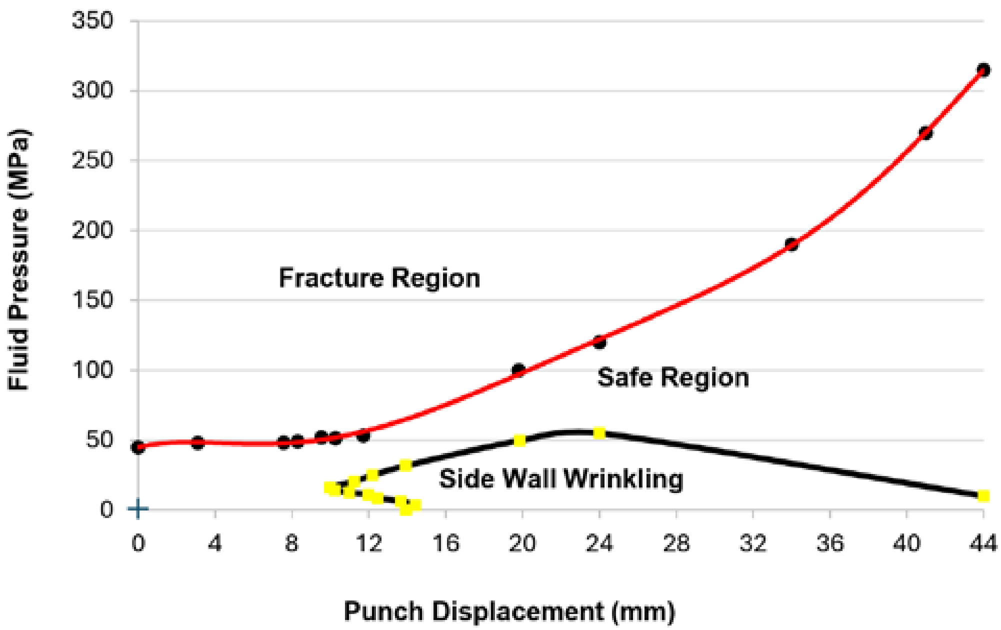
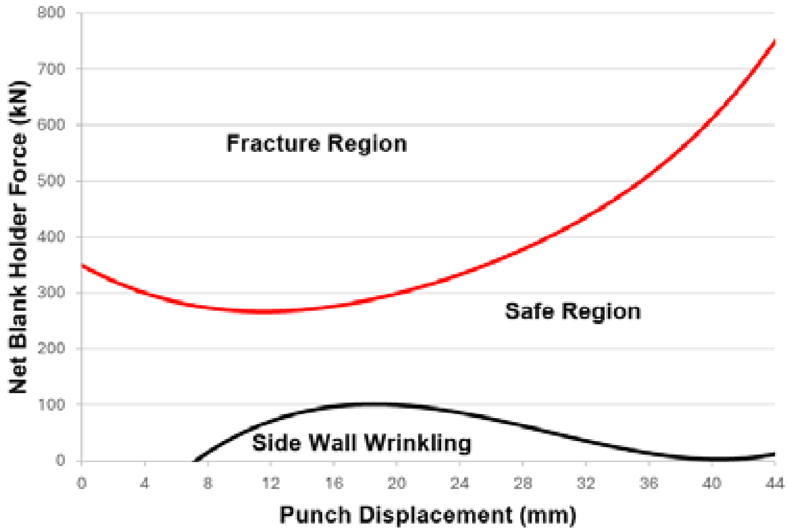


Figure 12

The process window for the blank holder force



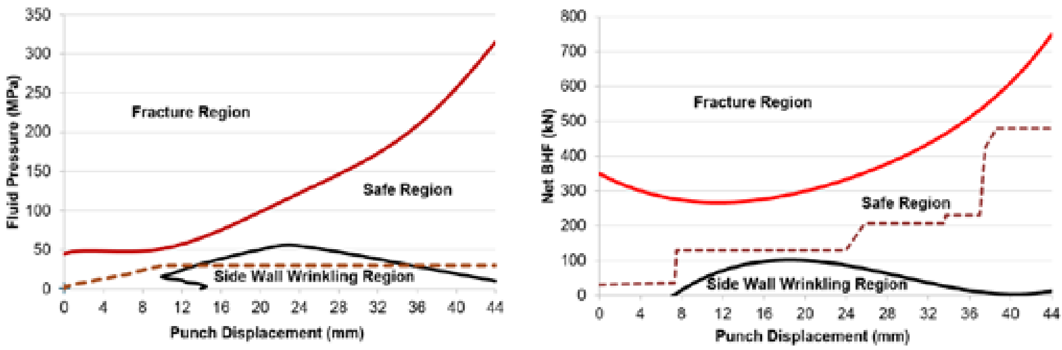
Verification of the Process Windows

HMDD experiments were conducted to validate the obtained process windows. Each experiment was repeated three times to verify its reliability. Experimental results that proved successful in all three repetitions were considered to validate the process window.

The first three experiments were performed to validate the fluid pressure process window. In these experiments, fluid pressure loading profiles were applied as they passed through the wrinkling and fracture regions, and blank holder force (BHF) loading profiles were applied through the safe region. So Experiment 1 was conducted using a pressure curve passing through the wrinkling region while maintaining the blank holder force (BHF) within the safe zone (Figure 13). Consequently, as shown in Figure 14, wrinkling defects occurred in the specimens, confirming the accuracy of the predicted wrinkling boundary.

Figure 13

The fluid pressure and net BHF loading profiles used in Experiment 1 were used to validate the wrinkling region of the fluid pressure process window.



In Experiment 2, validation was performed using a different profile passing through the boundary of the wrinkling region, as shown in Figure 15. For this experiment, the BHF curve used in Exp 1 that passes through the safe zone was employed. Experimental results again revealed wrinkling defects in the specimens, as illustrated in Figure 16. Based on the outcomes of Experiments 1 and 2, it was concluded that the wrinkling boundary of the fluid pressure process window was accurately determined.

Figure 14

Wrinkling defects occurred at Experiment 1 as expected

Figure 15

The fluid pressure loading profile used in Experiment 2 to define boundary of the fluid pressure process window.

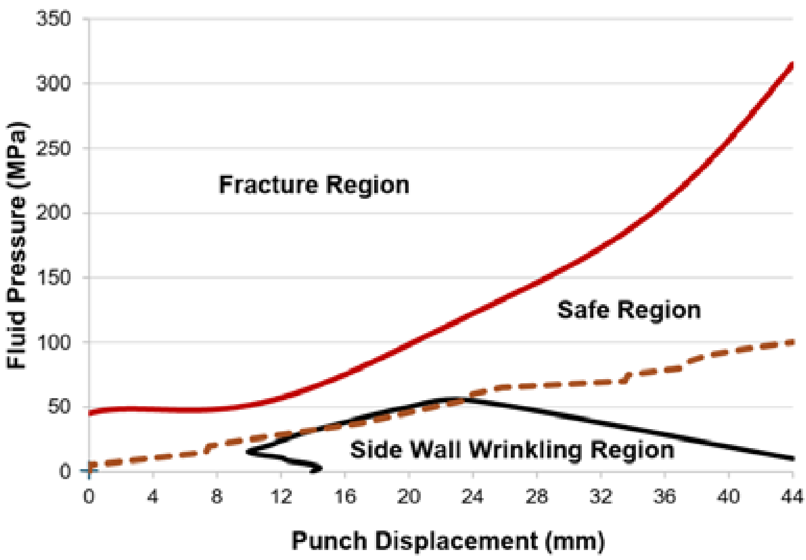


Figure 16

Wrinkling defects occurred at Experiment 2

In Experiment 3, a pressure curve passing through the fracture region was applied while maintaining the BHF curve within safe zone boundaries, as shown in Figure 17. As anticipated, fracture damage occurred in the product, as shown in Figure 18.

Figure 17

The fluid pressure and net BHF loading profiles used in Experiment 3 to validate the fracture region in the fluid pressure process window.

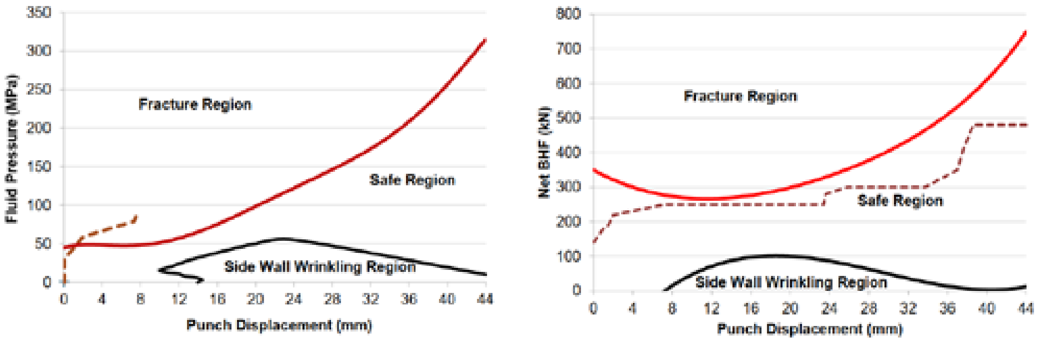


Figure 18

The parts were fractured after applying the loading curves in Figure 16 at Experiment 3

The first 3 experiments were conducted to verify the fluid pressure process window.

After the fluid pressure curves were verified, the latter experiments were performed to verify the BHF process window. So in Experiment 4, the loading profiles were applied as shown in Figure 19. In here to protect against the leakage of the fluid, the fluid pressure curve was passed through the lower boundary of the safe zone. BHF profiles were passed through the wrinkling zone. So the parts were formed with wrinkling defects as expected, as shown in Figure 20.

In Experiment 5, the pressure curve was maintained within the safe zone while the BHF curve was deliberately routed through the fracture boundary (Figure 21), with the expectation of inducing product fracture. As shown in Figure 21, the experiment resulted in specimen fracture as anticipated. Similar fractures occurred in Experiment 6 when the BHF loading profile was routed through the fracture boundary of the BHF process window, as shown in Figure 23. This confirms that the fracture regions for the blank holder force were accurately determined.

Figure 19

The fluid pressure and net BHF loading profiles used in Experiment 4 to validate the wrinling region of the BHF process window.

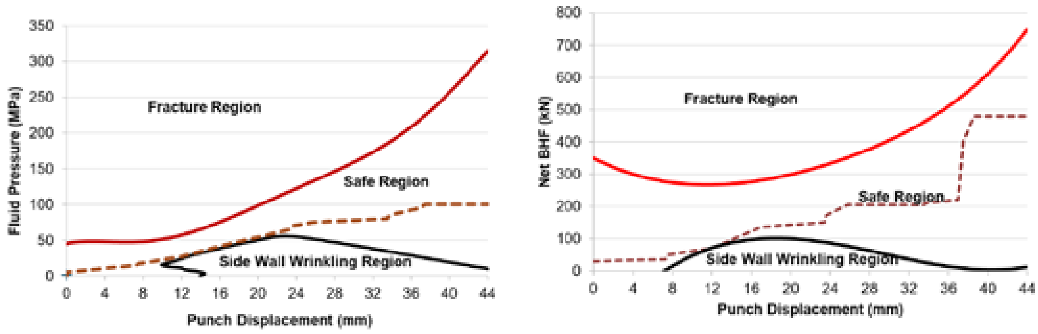


Figure 20

The parts were formed with wrinkling defects after applying the loading profiles in Figure 19 at Experiment 4.

Figure 21

The fluid pressure and net BHF loading profiles used in Experiment 5 to validate the fracture region of the BHF process window.

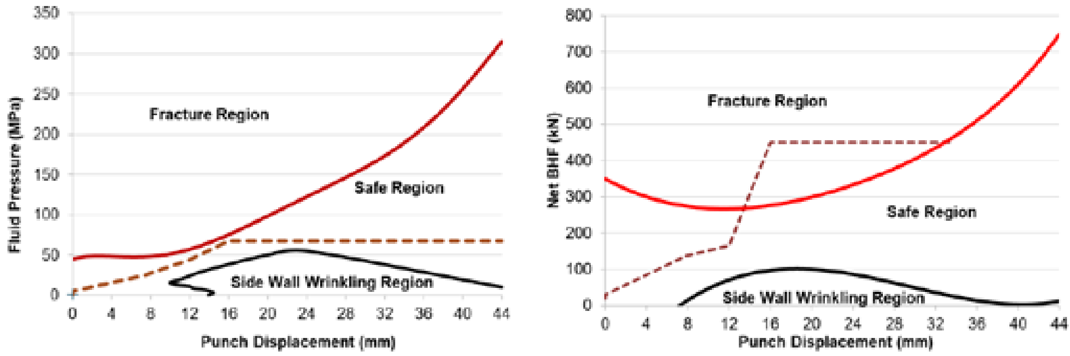
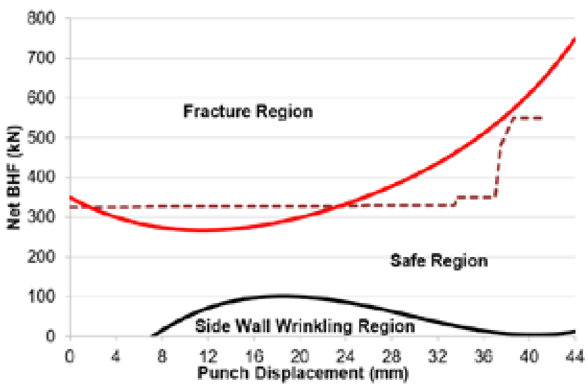


Figure 22

The parts were formed with fracture defects after applying the loading profiles in Figure 19 at Experiment 5.

Figure 23

The BHF loading profile applied in Experiment 6 to validate the boundaries of the fracture region in the BHF process window and fractured specimens.



The final experiments (Experiment 7) were conducted to verify the safe zones of both process windows. Therefore, loading profiles were applied as shown in Figure 24. The experimental results demonstrated that specimens could be manufactured without any wrinkling or fracture damage, as illustrated in Figure 25.

Figure 24

The loading profiles passed through the safe regions of both the fluid pressure and BHF process windows to successfully manufacture the part in Experiment 7.

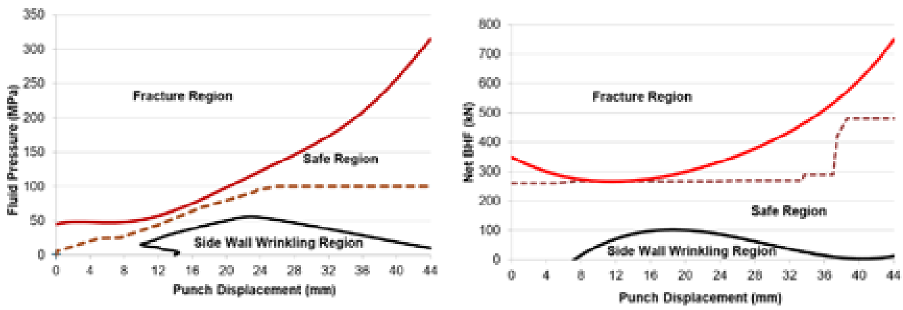


Figure 25

The specimens formed without wrinkles or defects in Experiment 7, using the loading profiles shown in Figure 24.

Conclusions

This study established and experimentally validated process windows for fluid pressure and blank holder force to prevent wrinkling and fracture defects in conical parts manufactured from AISI 304 stainless steel sheets via Hydromechanical Deep Drawing (HMDD).

Developing process windows is a time-consuming and challenging procedure that varies significantly with part geometry, material, and sheet thickness. It requires extensive trials across a wide parameter range to identify values ensuring successful part production. Given the high cost and time associated with experimental determination, numerical methods prove to be the most effective approach for establishing process windows. In this study, individual process windows for fluid pressure and blank holder force—key controllable parameters critical to successful forming—were developed as functions of punch position for a sample part produced by HMDD.

The key findings of this study are summarized below:

- The process windows developed for a specially shaped part were experimentally validated, confirming the effectiveness of the proposed methodology.
- Flawless part production was demonstrated using the established process windows.
- The safe zone in the fluid pressure process window was significantly narrower than that of the blank holder force window, indicating that fluid pressure requires much more precise control in the HMDD production of industrial parts.
- The process windows delineate the parameter limits for potential defects such as fracture, wall wrinkling, and flange wrinkling. The choice of failure criteria substantially influences the shape and boundaries of these windows.
- The absence of a standardized methodology and the case-specific nature of process windows position them as valuable know-how, particularly suitable for industrial applications.

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The Effect of High-Pressure Die Casting Parameters on the Microstructure and Mechanical Properties of A356 Aluminum Alloy

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Introduction

The casting method is widely used in various industries today for producing parts with complex geometries and high repeatability. Through sand casting, large and intricately shaped components that are unattainable by other processes can be manufactured economically. Among the diverse casting techniques, high-pressure die casting (HPDC) is frequently employed for parts requiring high production rates, tight tolerances, and good surface quality. The HPDC process enables the production of complex parts with minimal need for subsequent machining operations like material removal, making it suitable for mass production and ensuring reproducibility of parts.

High-pressure die casting is a process where molten metal is injected into a die cavity under high pressure. A wide range of critical components requiring precision, such as bicycle parts, cutlery, watches, air conditioners, ashtrays, hand tools, motors, locks, pulleys, valves, tractor and train components, electrical appliances, binoculars, air brake systems, military equipment, and rocket parts, can be produced via HPDC (Aslan, 2007). This method offers advantages like tight tolerances and excellent surface finish, allowing for dimensional tolerances of ±0.12 mm and surface roughness values as low as 0.5-3 µm. Eliminating the need for additional machining provides significant cost and time savings. Furthermore, the ability to produce thin-walled sections and achieve production rates of up to 500 parts per hour enhances the method's appeal. Despite its numerous advantages, drawbacks include high mold and machine costs and its primary suitability for metals with lower melting points, such as aluminum, magnesium, zinc, and tin.

High-pressure die casting is implemented in two main variants: hot-chamber and cold-chamber die casting. This system, first patented and applied in the early 1900s, generally consists of the die, piston, molten metal chamber, gas accumulator, and die locks. It is the most preferred method for metals with low melting points like zinc, magnesium, tin, and lead (Kaplan, 2012). This method can produce very small parts and achieve high surface precision, around ±0.05 mm. As the process operates between 70-350 bar, part surface accuracy is very high (Duran, 2014). Cold-chamber die casting is preferred for metals with melting points above 600°C, such as aluminum, magnesium, and copper. This method is also referred to as metal injection. Its primary advantage is that the high-temperature metal does not affect the piston-cylinder mechanism directly. The metal is melted in a separate furnace from the injection machine, ladled, and then poured into the machine's chamber. The pressure within the die cavity in this process typically ranges from approximately 50 to 1000 bar.

Successful high-pressure die casting requires the selection of appropriate process parameters, primarily casting temperature, pressure, and solidification time. Additionally, die and material parameters are crucial. Factors influencing the method can be categorized into three groups:

- A properly functioning casting mechanism with factors like applying and releasing suitable pressure.
- A correctly designed and manufactured die.
- A suitable alloy.

These characteristics must be evaluated not in isolation but as an integrated whole, ensuring coordinated control over the entire casting process (Aslan, 2007).

The literature contains studies investigating the effect of process parameters on the mechanical properties and quality of parts produced by high-pressure die casting. Among them, Wang et al. (2022) examined the effect of process parameters on mold filling and feeding for a part produced via HPDC from ADC12 aluminum alloy. Trials conducted with different metal temperatures and piston speeds were compared with simulations, leading to part production based on these comparisons. In the produced samples, the piston fast shot speed (2nd and 3rd phases) was found to have the most significant effect on melt filling and part feeding. It was noted that low melt temperature could easily lead to gas porosity. The effect of the the piston slow-shot speed (1st phase) on gas porosity was attributed to the entrapment of air from the injection chamber into the metal.

Jarfos et al. (2022) investigated the relationship between machine settings and in-cavity conditions to understand the transitions between different filling stages and the final intensification pressure settings. A pressure sensor was placed inside the die cavity to indirectly measure pressure development over time, monitor in-cavity conditions, and track the filling process. By analyzing the pressure-time profile, they studied the maximum pressure and pressure acceleration. The study concluded that using higher intensification pressures positively affected casting integrity. High intensification pressure was reported to have a more significant impact than the second-stage filling speed.

In their study, Zhang et al. (2021) investigated the effect of modifying piston motion curve profiles on mechanical properties. Tensile specimens produced via HPDC from A356 aluminum alloy were examined based on experimental and modeling results. Porosity prediction was performed through HPDC process simulation and validated with microstructural analysis. Results indicated that increased piston speed led to a more homogeneous distribution of oxides, resulting from fragmentation and transport of free-surface oxides. This reduced oxide distribution contributed to improved tensile properties in the cast specimens. Accordingly, increased piston speed was observed to lead to a tendency for reduced porosity distribution.

In a study conducted by Toptaş (2014), the feasibility of producing a pistol frame, originally manufactured by forging, using the high-pressure die casting method with a suitable raw material was investigated. Experiments were performed for appropriate raw material selection. It was found that when 6082 Al alloy was subjected to T5 and T6 heat treatments, the properties achieved reached strength levels comparable to those of HPDC products after die casting followed by quenching. Productions with and without vacuum application were carried out, confirming that vacuum application eliminated internal voids formed within the parts.

In the study by Yalçın et al. (2012), eight different parameters were tested by varying casting pressure, casting speed, and product cooling method. It was determined that part quality increased when the injection parameters for the high-pressure die casting of Etial 150 aluminum alloy were set to an injection speed ratio of 100% and an injection pressure of 150 bar, coupled with water cooling of the ejected parts. Water cooling of the produced specimen resulted in a 3% increase in strength.

The examined studies demonstrate different yet complementary approaches to HPDC process optimization. These studies confirm the strong connection between process parameters, microstructure, and mechanical performance, forming the scientific foundation upon which this research is based.

This study is derived from a MSc thesis (Tekin, 2022) that investigated the feasibility of producing a passenger car stabilizer bar, traditionally manufactured by forging, using the aluminum high-pressure die casting (HPDC) process. The primary goal was to analyze and resolve the fracture problem occurring during the component's essential 'cover closing' forming operation. The overall research was conducted in two distinct phases: the first focused on the effect of HPDC parameters on the mechanical properties of the A356 alloy, and the second involved product-driven process optimization through die design simulation, production, and functional testing. This paper presents the results of the first phase: a systematic investigation into how HPDC process parameters influence the mechanical properties of the A356 aluminum alloy.

Materials and Experimental Procedure

Material and Melt Preparation

The A356 (AlSi7Mg) aluminum alloy was used in this study. The chemical composition of the A356 series Al-Si7Mg alloy is given in Table 1. This alloy is frequently preferred in aluminum casting methods. This material is known for its high fluidity and sufficient strength. Additionally, the material offers suitability for plastic forming thanks to its adequate ductility.

Table 1

Chemical composition of A356-0 aluminum alloy

Si	Fe	Cu	Zn	Mn	Mg	Ti	Other	Al
6.5-7.5	0.20	0.2	0.1	0.1	0.25-0.45	0.20	0.15	the rest

The alloy was melted in a 600 kg capacity natural gas-fired tilting furnace (Figure 1) at 720°C. The chemical composition of the melt was verified using spectrometry to ensure material conformity. To eliminate dissolved gases, particularly hydrogen, the molten metal was degassed in a 250 kg ladle (Figure 2) using a rotary degasser with nitrogen gas for 180-220 seconds at 600 RPM. The melt quality was assessed by comparing the densities of two samples solidified under vacuum and atmospheric pressure, respectively, using a vacuum density test instrument (Figure 3). A lower density difference indicates a cleaner, degassed melt.

Figure 1

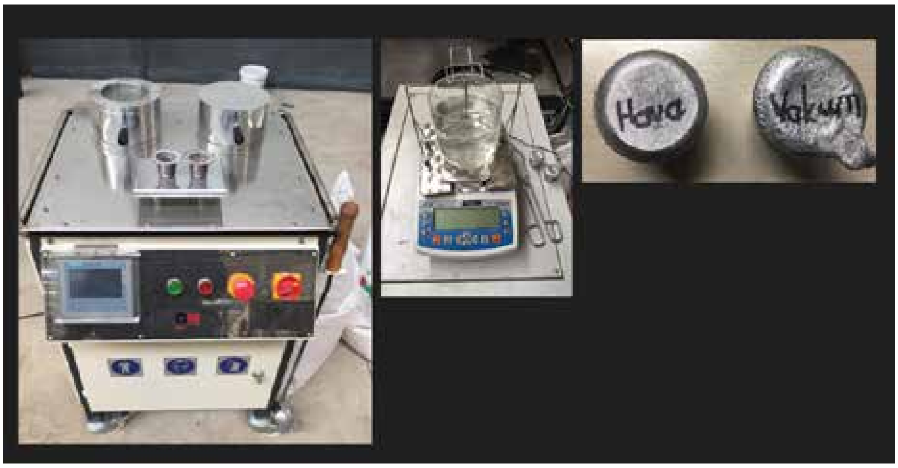
Tilting type melting furnace

Figure 2

Degassing process using nitrogen gas

Figure 3

Vacuum density tester



High Pressure Die Casting (HPDC) Process

The HPDC experiments were conducted on an Era press cold-chamber die casting machine (Figure 4) with a 7720 kN clamping force and a 60 mm diameter piston. The injection process, controlled by a PLC, occurs in three phases (Duran, 2014):

- First Phase (Slow Shot): The molten metal advances slowly to the gate.

- Second Phase (Fast Shot): The metal is injected into the die cavity at high velocity.

- Third Phase (Intensification): High pressure is applied to feed the solidified casting.

To avoid confusion in the literature regarding pressure definitions, this study uses the specific injection pressure (the pressure exerted by the piston on the molten metal in the chamber) as the relevant parameter.

Figure 4

Cold chamber horizontal injection press

Experimental Design and Tensile Sample Extraction

A Taguchi L9 orthogonal array was employed to efficiently study the effects of three parameters at three levels each (Table 2): melt temperature, injection velocity (second phase), and intensification pressure. The experimental design is shown in Table 3. For each of the nine parameter sets, five repetitions were produced, totaling 45 castings. To ensure process stability, three initial shots were discarded after each parameter change before collecting samples for testing. Tensile test specimens were machined from the cylindrical central section of the cast stabilizer bars, as illustrated in Figure 5. The overall HPDC process flow is summarized in Figure 6 and a photograph of the final cast parts is provided in Figure 7.

Table 2

Parameter levels used in the experiments

	1	**2**	**3**
Temperature (°C)	700	720	740
Velocity (m/s)	2	2.5	3
Pressure (bar)	850	1010	1290

Table 3

Experimental design (L9 Array)

Exp. Number	Temperature (°C)	Velocity (m/s)	Pressure (bar)
1	700	2	850
2	700	2.5	1010
3	700	3	1290
4	720	2	1010
5	720	2.5	1290
6	720	3	850
7	740	2	1290
8	740	2.5	850
9	740	3	1010

Figure 5

Stabilizer Bar Manufactured by HPDC Process

Figure 6

Flow Chart of the HPDC Process

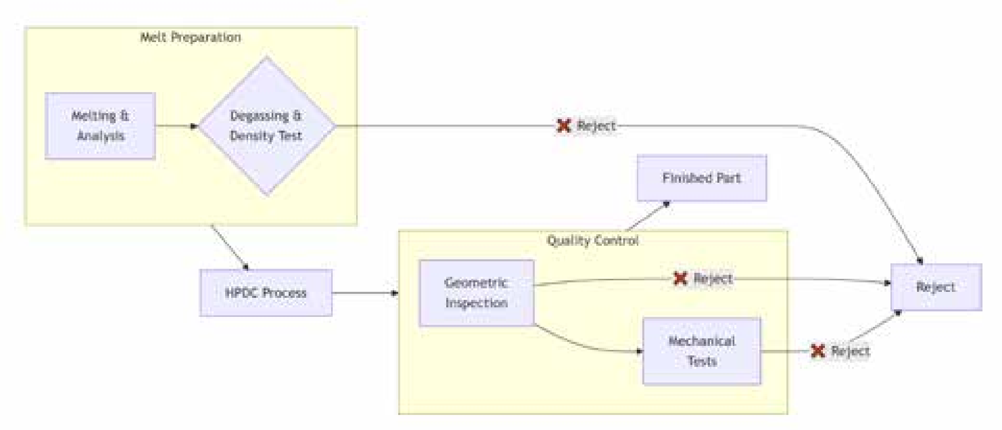
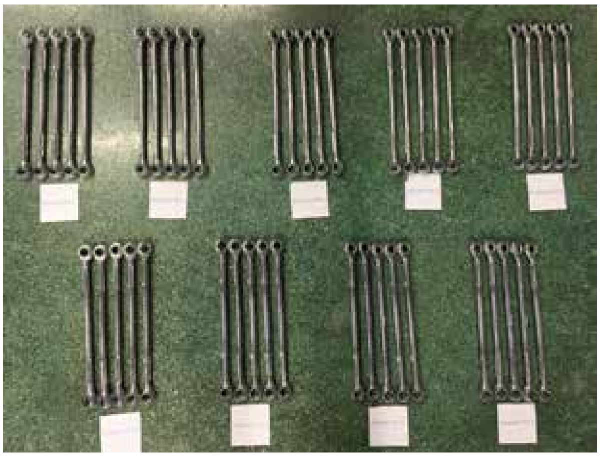


Figure 7

Test strips produced for 9 different test parameters



Tensile test specimens were machined from the cylindrical central section of the cast stabilizer bars. The tensile bars were processed on a CNC lathe to the dimensions specified in the ASTM E8 standard (Figure 8). Subsequently, the threads at both ends were formed on a thread rolling machine to prepare the specimens for tensile testing (Figure 9).

Figure 8

Dimensions of the manufactured tensile test specimen

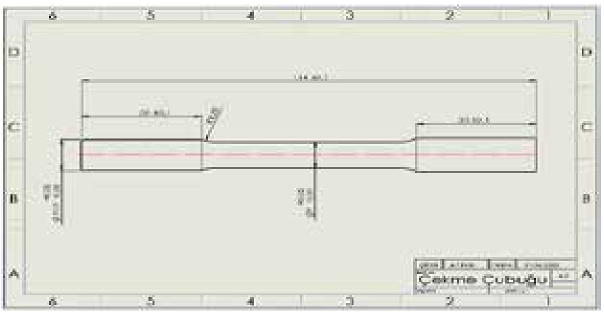


Figure 9

Ready-made tensile bar and grouped samples

Tensile tests were conducted at room temperature at a speed of 5 mm/min using a Devotrans DVTNU model 100 kN capacity testing machine.

Microstructural Characterization

Sections for microstructural analysis were carefully extracted from the HPDC specimens using an abrasive cutting machine with water cooling to prevent microstructural alterations from heat buildup.

The sectioned samples were then mounted in bakelite and prepared using a Buhler brand grinding and polishing machine. The preparation procedure was performed as follows:

1. **Grinding:** A sequential grinding process was conducted using 180, 320, 500, 800, 1200, and 2400 grit abrasive papers.
2. **Polishing:** The ground samples were subsequently polished using a 3 µm diamond suspension for rough polishing, followed by a final polishing step with a 0.87 µm silica suspension.
3. **Etching:** To reveal the microstructure, the polished surfaces were etched using an aluminum micro-etchant with a composition of 0.5% HF and 99.5% distilled water.

The prepared samples were examined using a Nikon ECLIPSE MA200 optical microscope. Microstructural images were captured at 100x magnification (200 µm scale).

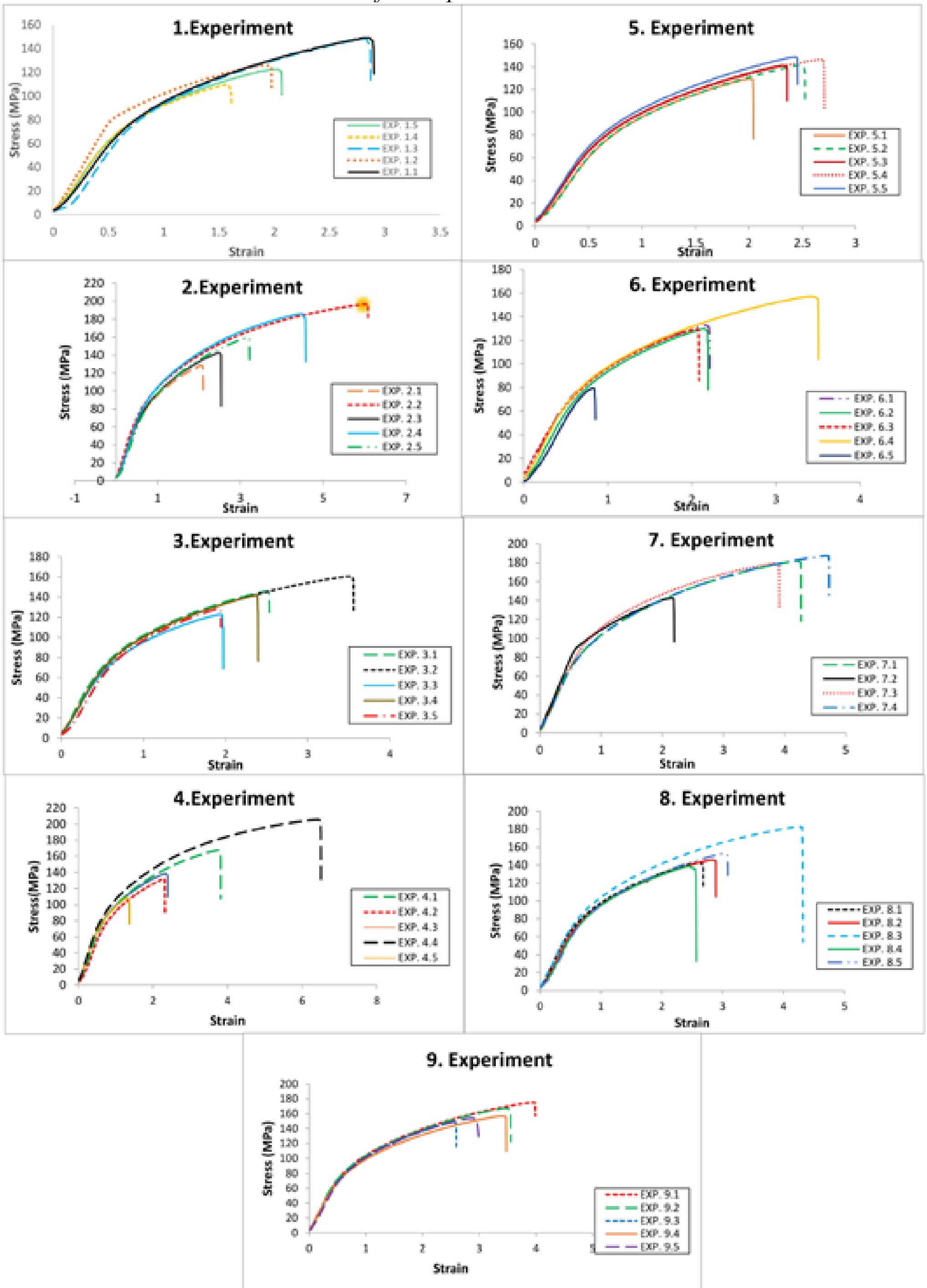
Results and Discussion

Tensile tests were conducted on specimens prepared from stabilizer bars produced under nine different conditions according to the Taguchi L9 experimental design. The results are presented in Figure 10. Each experiment was repeated five times, and the graphs show the

stress-strain curves for all repetitions. The graphs indicate no significant differences in yield strength among the replicates. Furthermore, the yield curves for almost all repetitions overlapped. However, some replicates showed considerable deviation from the average in terms of ultimate tensile strength and percent elongation. Although produced under the same conditions, differences were observed in the mechanical properties of the samples. It is thought that uncontrolled factors caused some test results to be very close to each other, while others differed.

Figure 10

Results of all repeated tensile tests



After the tensile tests, it was determined that brittle fractures occurred in the tensile specimens, as seen in Figure 11. In the HPDC process, the likelihood of porosity formation is very high due to aluminum's affinity for hydrogen. It is thought that this situation causes different porosity levels in the samples produced in each cycle, consequently leading to variations in ductility values. Therefore, differences exist between the replicates of the same experiment. A representative tensile test curve, taken as the average for each experiment, was used to compare the tensile curves of parts produced under different manufacturing conditions, as shown in Figure 12.

Figure 11

Fracture Surface Images After the Tensile Test

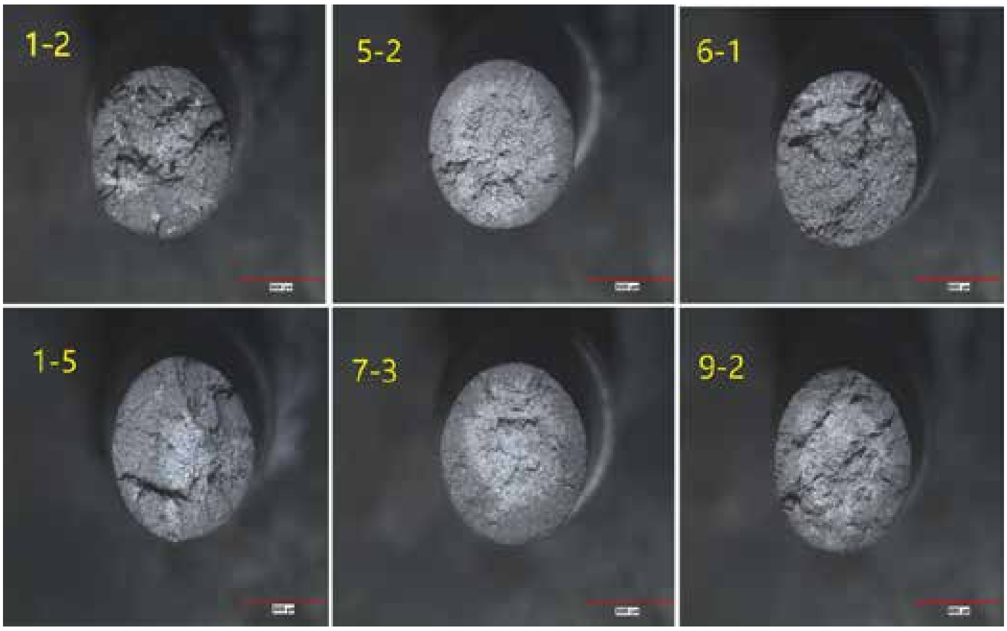
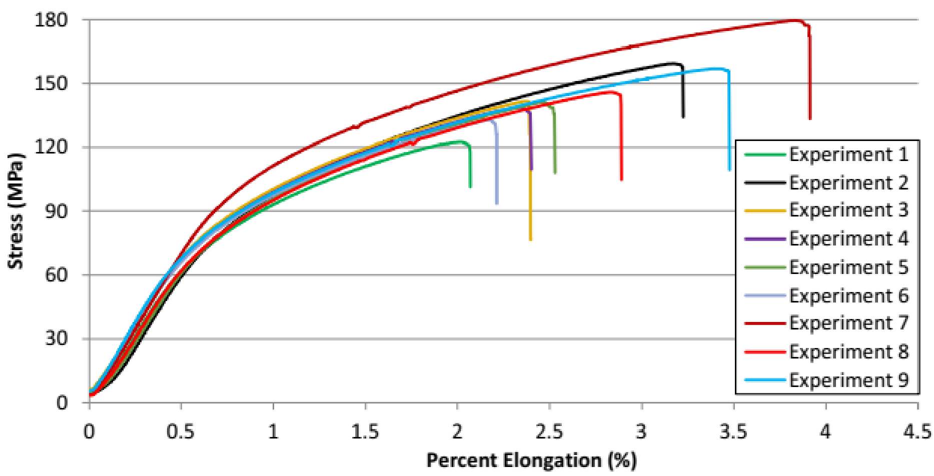


Figure 12

Comparison of the Average Tensile Curves for the Nine Different Experiments Conducted According to the Experimental Design Matrix



According to the results, the highest yield strength was observed for parts produced in Experiment 7, which used the highest temperature (740°C), the lowest speed (2 m/s), and the highest pressure (1290 bar). These specimens also exhibited higher yield and tensile strength, as well as higher percentage elongation values compared to those produced under other conditions. In contrast, the worst mechanical properties were obtained for parts produced in Experiment 1, which used the lowest temperature (700°C), the lowest speed (2 m/s), and the lowest pressure (850 bar). While there was no significant difference in stress levels among the yield curves from other experiments, differences occurred in the percentage elongation.

To investigate the effect of process parameters on mechanical properties in more detail, the yield strength, percentage elongation, and plastic strain values obtained from each experiment were calculated, compared and analyzed using ANOVA. The yield strengths calculated from the tensile tests are compared in Figure 13. The bar charts in the figure show the average values for the experiments, and the scatter of the data is shown as error bars on each column. When creating the graph, the values that deviated the most from the average were discarded, and the results of at least three values closest to the average were used. The numerical values of the results are given in Table 4

Figure 13

Comparison of the Average Yield Strengths of the Experiments

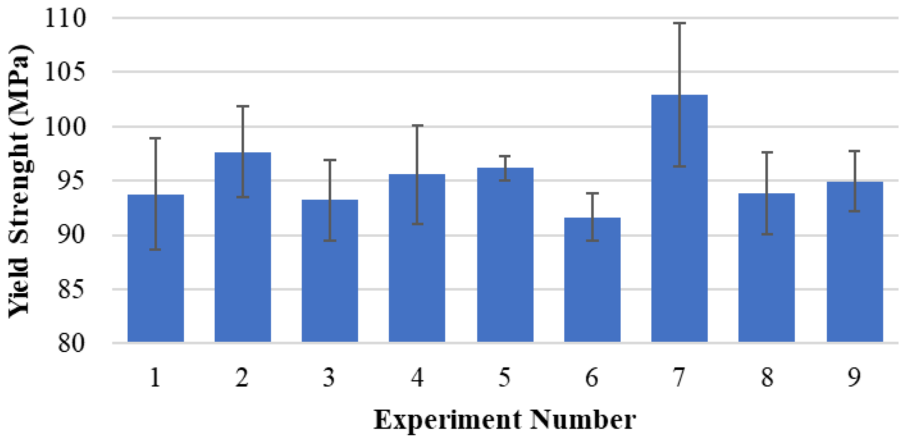


Table 4

Yield strength values

Yield Strength (MPa)	1	2	3	4	5	6	7	8	9
1. Repetition	97.57	93.17	91.81	99.41	96	90.2	96.2	89.63	96.2
2. Repetition	94.3	95.45	95.25	95.5	96.26	89.78	103.02	92.06	94.43
3. Repetition	87.98	95.63	97.1	100.5	95.04	92.06	100.68	95.39	96.97
4. Repetition	89.24	101.15		92.84	95.56				96.8
Average	**92.27**	**96.35**	**94.72**	**97.06**	**95.72**	**90.68**	**99.97**	**92.36**	**96.10**
Std Dev	**4.46**	**3.39**	**2.68**	**3.54**	**0.53**	**1.21**	**3.47**	**2.89**	**1.16**

The average yield strength ranged from a minimum of 90.7 MPa to a maximum of 100 MPa. Analysis of variance (ANOVA) was performed to determine the effect of the parameters on yield strength, and the results are given in Table 5. According to the ANOVA results, only the pressure parameter had a P-value less than 0.05. Therefore, it was concluded that only the pressure parameter had a statistically significant effect on yield strength. Since the P-values of the other parameters were greater than 0.05, it was determined that the temperature and speed parameters did not have a significant effect on yield strength. The contribution percentage of the pressure parameter to the yield strength was approximately 73%. The R^2(adj) value, representing the reliability of the system from the regression analysis, was 88.74%. While values of 70% and above are considered acceptable in engineering problems, 88.74% clearly indicates that the experiments and analyses are highly reliable. The main effects plots for the parameters on yield strength are shown in Figure 14. Accordingly, it is observed that as the pressure, which is the most influential parameter, increases, the yield strength also increases. Therefore, it was concluded that the most suitable pressure value for the production of the stabilizer bar, among the selected levels, is 1290 bar. Although no significant effect of temperature and speed parameters on yield strength was found, it can be said that high temperature and low speeds tend to increase the yield strength. This situation can be explained by the reduction in porosity formation at high temperatures, low speeds, and high pressures.

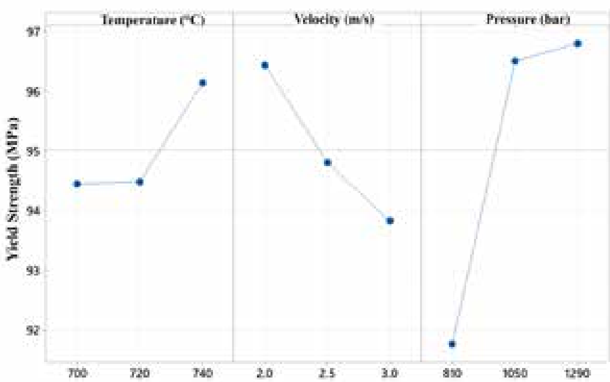
Table 5

Results of the Analysis of Variance (ANOVA) Performed on the Yield Strength

Parameter	Degrees of Freedom	Sum of Squares	Contribution %	Mean Square	F-value	P-value
Temperature	2	5.616	8.56%	2.8078	3.04	0.247
Velocity (m/s)	2	10.356	15.78%	5.1781	5.61	0.151
Pressure (bar)	2	47.795	72.84%	23.8974	25.89	**0.037**
Error	2	1.846	2.81%	0.9231		
Total	**8**	**65.613**	**100.00%**			

Figure 14

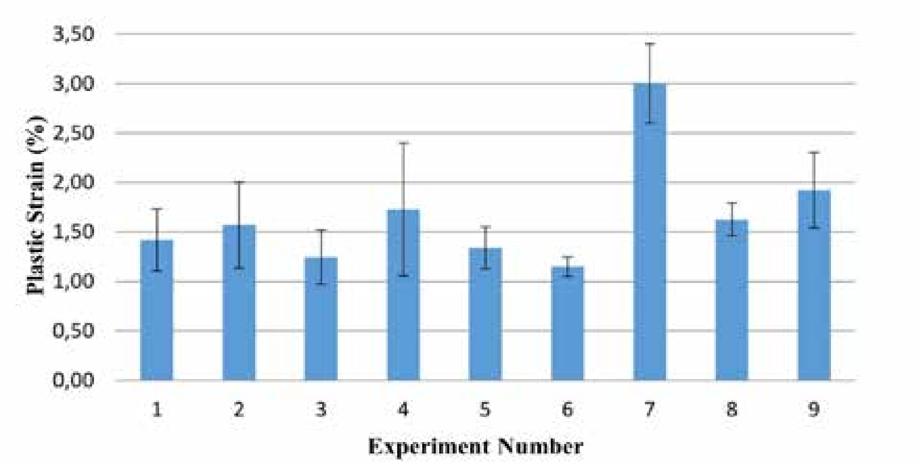
Main Effects Plot for Yield Strength



In a tensile test, the elongation that occurs from the point the material begins to yield until its fracture is termed plastic strain. Since the study aimed to investigate the effect of die-casting parameters on the plastic deformation behavior of the material, the plastic strain values, rather than the total percentage elongation, were taken as the performance criterion. The plastic strain values obtained from the experiments, conducted with five repetitions for each of the nine different experimental conditions, are presented in Figure 15.

Figure 15

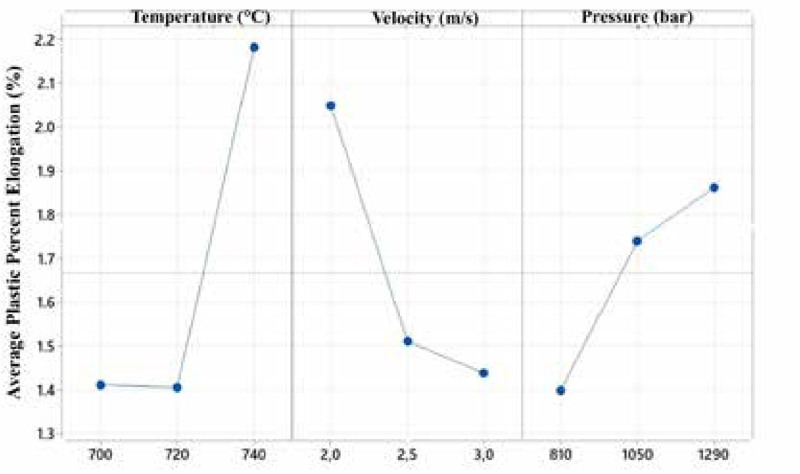
Plastic Strain Values (%) for the Nine Experiments



The plastic strain varied between 1.15% and 3%. The highest elongation was obtained at the highest temperature, highest pressure, and lowest speed parameters, while the lowest elongation occurred at the highest speed, lowest pressure, and medium temperature level. From this, it can be said that the most suitable parameters for the plastic deformation capability of the stabilizer bar produced from A356 aluminum alloy are the highest pressure, lowest speed, and highest temperature levels.

Figure 16

Main Effects Plot of Parameters on Plastic Strain



When ANOVA was performed on the experimental results to investigate the effects of the parameters in more detail, it was seen that statistically significant results were not obtained because the P-values of the parameters at the selected levels were above 0.05. The R^2(adj) value from the regression analysis, representing the reliability of the experimental results, was 57.7%. Therefore, it was evaluated that the main effects plots given in Figure 16 can be used to approximate the effect of the parameters on plastic strain.

An increase in temperature from 700°C to 720°C did not cause a change in plastic strain; however, an increase from 720°C to 740°C caused a 57% increase in plastic strain. Increasing the speed from 2 m/s to 2.5 m/s resulted in a 25% decrease in plastic strain. When the speed was increased from 2.5 m/s to 3 m/s, the decrease in plastic strain continued. Increasing the pressure from 850 bar to 1290 bar contributed to a 32% increase in plastic strain. Thus, it was concluded that temperature has a greater effect on plastic strain than the other two parameters, and that high temperatures, high pressure, and low speed are more suitable for the plastic deformation capability of the A356 alloy.

Microstructural Analysis Results

To investigate the effect of process parameters on mechanical properties more comprehensively, microstructural images and fracture surfaces were obtained for selected experiments. Figure 17 presents etched micrographs at 100x magnification for Experiments 1, 5, 6, 7, and 9, revealing grain boundaries and secondary phases.

In the microstructure, the light-toned areas correspond to the α-aluminum phase, while the needle-like structures are the eutectic silicon phases. Although the secondary phases are generally distributed evenly along the grain boundaries, some localized clustering is observed. Furthermore, as seen in Figure 18, grey regions in the microstructure were identified as the β-Al_5FeSi phase. This intermetallic phase forms due to the low solubility of iron in aluminum and is highly brittle, consequently reducing the ductility of the material. Some black areas, indicating porosity, were also observed within the structure, albeit in small amounts. Porosity primarily occurs due to the easy dissolution and subsequent release of hydrogen in aluminum. Although the amount was limited, it is believed that these microporosities contributed to the significant variation in ductility observed between experimental replicates. Dendritic growth arms were visible in some samples. In conclusion, the microstructural examination revealed that, in general, the grain size, secondary phase morphology, and distribution were similar across the different experiments. This observation is consistent with the absence of major differences in mechanical properties between the experimental conditions.

Figure 17

Microstructural Images of the Tested Specimens

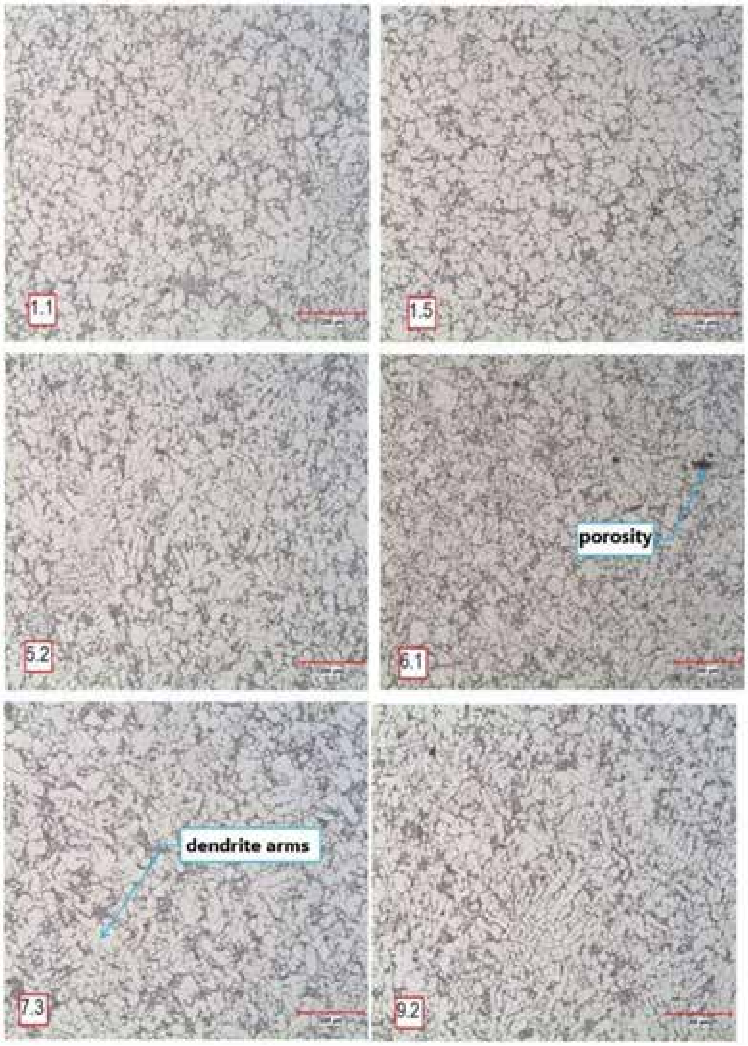
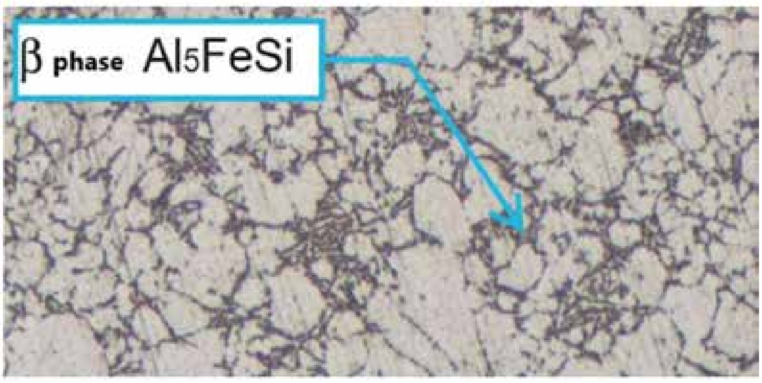


Figure 18

β-Al_5FeSi phase in the Microstructure



Conclusions and Recommendations

Conclusions

This study investigated the effect of process parameters of the high-pressure die casting (HPDC) method on the mechanical properties of A356 (AlSi7Mg) alloy. The die casting process was carried out according to a Taguchi L9 experimental design array, varying three levels of temperature, pressure, and velocity.After the tensile test specimens prepared from the cast parts, and tensile tests were conducted with five repetitions for each condition to investigate the effect of process parameters on yield strength, ultimate tensile strength, and plastic strain. Analysis of the tensile test results via ANOVA revealed that, statistically, only the pressure parameter had a significant effect on yield strength. The yield strength ranged from a minimum of 90.7 MPa to a maximum of 100 MPa. Pressure was responsible for 73% of the variation in yield strength, with a 5% increase observed as pressure rose. The ultimate tensile strength varied between 130 MPa and 185 MPa, generally achieving higher values at combinations of low temperature, low speed, and high pressure, which can be attributed to reduced porosity formation under these conditions. The plastic strain varied between 1.15% and 3%. It was concluded that the highest pressure, lowest speed, and highest temperature levels are the most suitable parameters for enhancing the plastic deformation capability of the A356 stabilizer bar.

Apart from the effect of pressure on yield strength, no clear and significant influence of the parameters was observed on the ultimate tensile strength and plastic strain. The microstructural investigation revealed that the grain size, secondary phase morphology, and distribution were generally similar across all experiments. This microstructural homogeneity is the primary reason for the lack of significant variation in mechanical properties. This similarity is likely because the differences between the selected parameter levels were insufficient to alter the microstructure significantly. Furthermore, it was concluded that the inherent uncertainty introduced by sporadic porosity formation also masked the potential effects of the process parameters.

Recommendations

To guide future research on high-pressure die casting, the following recommendations are proposed:

- The temperature parameter range could be widened to potentially induce more noticeable differences in the performance criteria.
- The chemical composition of the casting alloy could be modified to achieve higher ductility. Research into chemical compositions that enhance ductility is recommended.
- The effectiveness of the degassing process for removing dissolved gases, such as hydrogen, from the molten metal should be investigated. The optimal values for nitrogen gas volume, impeller rotation speed, and degassing duration could be studied to determine their specific impact on porosity formation.
- The effect of heat treatments on the mechanical properties of the produced castings should be investigated.

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Analysis of Biomass-Based Energy Conversion Technologies: Current Trends and Evaluations

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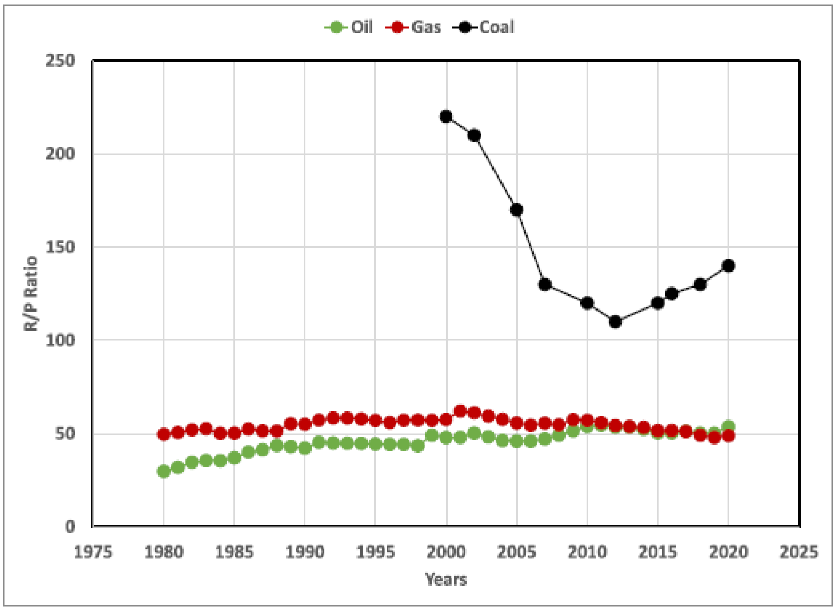
Introduction

The use of fossil fuels dates back approximately 225 years (Kelkar, 2024). Technological advances have increased energy demand, and over the years, more fossil fuels have been extracted and used to meet this demand. **Figure 1** shows the ratio of oil, gas and coal reserves to production volumes over the last 40 years. An examination of the figure reveals that this ratio remained around 50 for oil and natural gas, while for coal it decreased and then increased from 2000 onwards, reaching around 150 in 2020. This means that, considering current demand levels, oil and natural gas have a remaining lifespan of 50 years each, while coal has a remaining lifespan of 150 years.

Figure 1

Reserve-to-Production Ratio for Oil, Natural Gas and Coal (last 40 years (Kelkar, 2024)



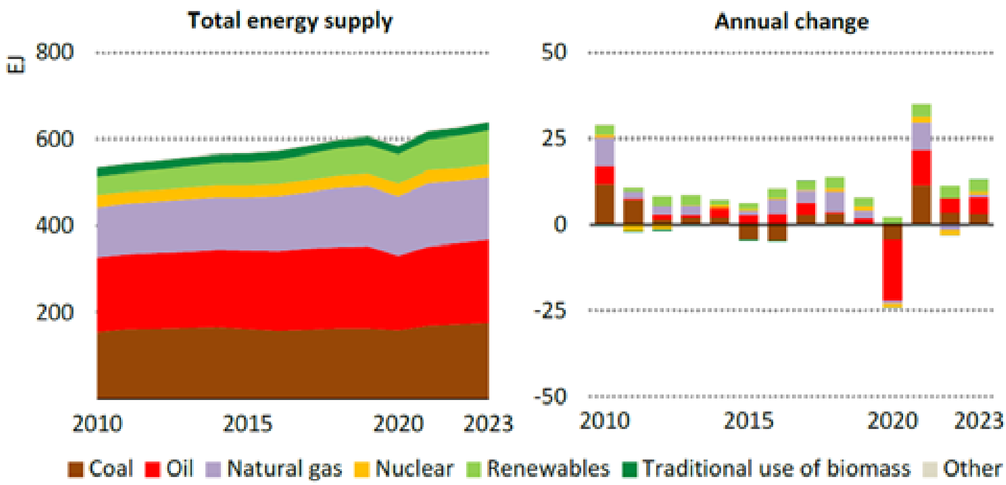
On the other hand, the sustainability of a fuel is of great importance for the future of the world. Researchers have recently placed great emphasis on sustainability and are conducting studies to ensure sustainability (Koul, Yakoob, & Shah, 2022), (Thirumalaivasan, Nangan, Kanagaraj, & Rajendran, 2024), (Happs et al., 2024), (Karvounis, Theotokatos, & Boulougouris, 2024), (Mehra, Goel, & Kumar, 2024), (Mbiankeu Nguea & Hervé Kaffo Fotio, 2024). The environmental sustainability of a material can be linked to its carbon footprint level(Akhtar, Krepl, & Ivanova, 2018). In this context, the sustainability of fossil fuels, which emit significant amounts of CO_2 into the environment when burned, thereby maintaining a very high carbon footprint level, is open to debate.

After the Industrial Revolution, fossil fuel use increased significantly, and atmospheric carbon concentration naturally increased as well. At the beginning of the Industrial Revolution, the atmospheric carbon concentration was 280 ppm, whereas it is currently at 420 ppm, and scientists predict that this value could reach 700 ppm by 2080. This situation causes climate change and leads to various health problems (Kabinesh et al., 2025). However, 85% of the world's energy needs are still met by carbon-based fuels. Meeting this need results in the annual release of 36 million tonnes of CO_2 into the atmosphere (Worku et al., 2024).

The use of renewable energy sources is increasing day by day. The graph in **Figure 2** is taken from the IEA 2024 report and shows the change in the global energy sources. The graph clearly shows that global energy usage are increasing (International Energy Agency, 2024). It is encouraging to note that the share of renewable energy sources has also increased to meet this growing demand.

Figure 2

World total energy demand 2010–2023 (International Energy Agency, 2024)



Renewable energy can be defined as an energy source that can be reused shortly after use, meaning it constantly renews itself over a short period of time. These energy sources include geothermal, solar, hydroelectric, wind, and biomass (Ibitoye, Mahamood, Jen, Loha, & Akinlabi, 2023). Research and applications have shown that renewable energy conversion technologies have developed significantly in recent times (Fang, Jiang, Li, Bai, & Chang, 2020), (Maheshwari, Kengne, & Bhat, 2023), (Irfan Sadaq, Mehdi, & Mohinoddin, 2023).

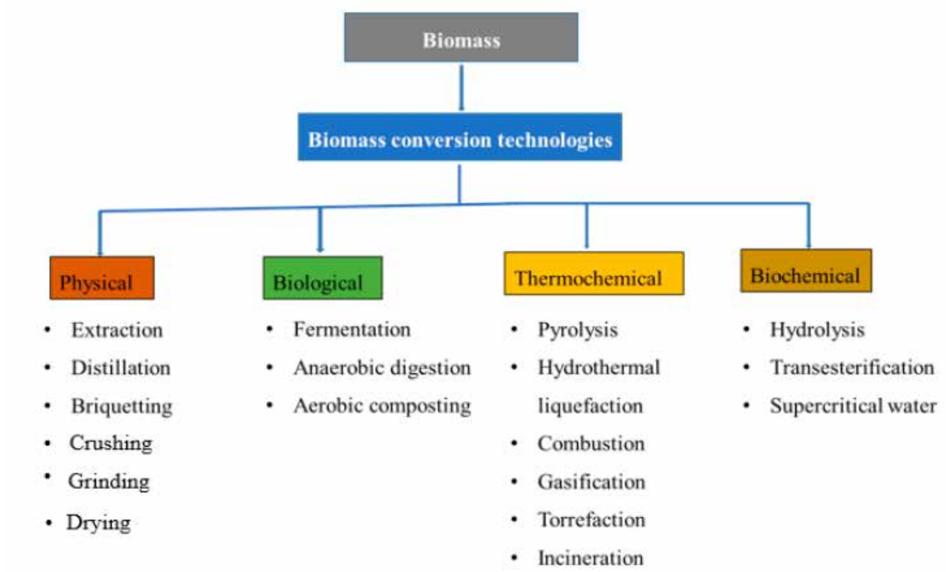
Among these renewable energy sources, biomass stands out due to its storability and its ability to be supplied throughout the year, at any time of day, with minimal impact from climate and season. Biomass is an energy source with a renewal period of approximately one year that reduces air pollution when used and slows the increase in atmospheric CO_2 content (Fülöp & Ecker, 2020).

Biomass resources can be categorized under three headings: waste, forest products, and energy crops (Ozturk et al., 2017). Biomass can be transformed into three primary outputs., two of which are energy-related. These are heat/power production, fuels for transport, and chemical precursors. To transform biomass from waste into a useful product, it must be converted using specific techniques. The type and quantity of product produced will be determined by the chosen technique. Therefore, the method chosen in the biomass conversion process is of great importance. Two main technologies can be identified for the conversion of biomass into energy: thermochemical and biochemical conversion (Mckendry, 2002). In addition, physical and biological conversion techniques are also used.In this study, current research on biomass energy conversion processes was examined and an evaluation of efficiency improvement applications was made.

Overview Of Biomass-Based Energy Conversion Technologies

Several fundamental techniques stand out in biomass conversion. Studies on this topic have developed in parallel with technological advancements and continue to evolve. In light of new technologies, new techniques have emerged, and efforts have been made to improve biomass properties. This section of the study provides an assessment of conversion processes implemented in recent years. A review of the literature reveals that physical, biological, thermochemical, and biochemical techniques are used as conversion techniques. **Figure 3** provides a synopsis of conversion techniques.

Figure 3
The conversion technologies in biomass (Tshikovhi & Motaung, 2023)



Choosing these techniques is contingent on certain parameters such as the type of final product, biomass quality, quantity, and economics (El-Fawal et al., 2025). For dry biomass, properties including moisture level, heating value, and volatile fraction, ash content, and alkali metal content influence the choice of conversion technology. In the case of wet biomass, its moisture content and the cellulose/lignin balance influence this selection. (Mckendry, 2002).

Physical transformation techniques are primarily related to size reduction, consolidation, drying and densification processes. Among the most preferred methods within this technique are briquetting, drying and extraction (El-Fawal et al., 2025). Among biological conversion techniques, the most preferred method is anaerobic digestion. Fermentation generally uses microorganisms to produce bioethanol, biogas, and biohydrogen (Munasinghe & Khanal, 2010). The following sections will focus on thermochemical and biochemical conversion methods.

Thermochemical Conversion Methods

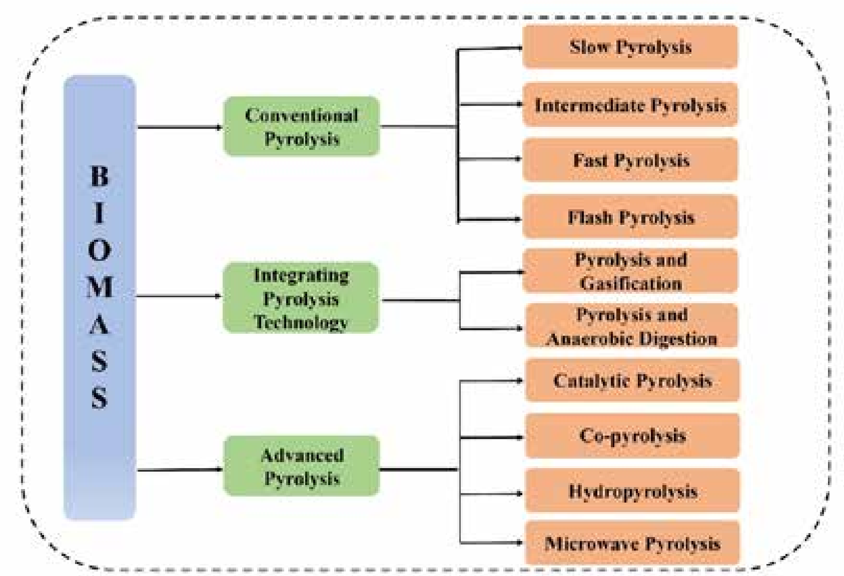
Thermochemical conversion methods play an important role in energy concentration by converting biomass resources into bio-oil and facilitate a carbon-neutral cycle (X. Zhang et al., 2025).

Pyrolysis

Pyrolysis involves the thermal disintegration of biomass in an oxygen-deficient environment. The process produces solid residue, liquid (bio-oil and water), and gas. This solid output, frequently referred to as biochar or charcoal, is a porous, carbon-dominant compound. (Suopajärvi et al., 2018). The traditional pyrolysis method can be divided into fast, slow, and flash pyrolysis processes (Shen, Wang, Ge, & Chen, 2016). Another pyrolysis classification by Cai et al. is shown in **Figure 4** (Cai et al., 2024). Here, new methods are listed alongside traditional pyrolysis.

Figure 4

Pyrolysis classification by (Cai et al., 2024)



The pyrolysis of biomass has attracted considerable interest as a technology capable of simultaneously producing high-value-added energy and chemical products such as bio-oil, biochar, and combustible gas. It has been observed that catalysts also play a role in pyrolysis and that catalysts improve the distribution and properties of pyrolysis products (Cai et al., 2024). Studies have also demonstrated the effect of the catalytic method on fast pyrolysis, which is a subcategory of pyrolysis. Catalytic fast pyrolysis is a complex technology influenced by various parameters, including composition, interactions between components, catalysts, process, reactor, and biomass type or pretreatment method (El Bari et al., 2024).

Microwave-assisted pyrolysis is a technique that has recently gained popularity. It appears to be advantageous due to its high heating rate and ease of use. However, its potential for converting various biomass materials into biofuels has not yet been fully explored. Studies on this topic are ongoing (Bisht et al., 2026). Recent studies have focused on various types of pyrolysis. These include new and innovative techniques. Microwave-assisted pyrolysis, catalytic pyrolysis, and co-pyrolysis are among the areas where research in the literature is concentrated. The table below summarizes some of the studies conducted on this topic.

Table 1

Summary information on some studies related to the pyrolysis method

Pyrolysis type	Biomass type	Year	Pyrolysis Parameter	Result	References
Catalytic pyrolysis	Burnt pine trees	2022	Fixed-bed reactor for temperatures of 673-773 K	Increasing the pyrolysis temperature resulted in a lower bio-oil yield from the burnt biomass. The biochar yield, however, was higher.	(Soares Dias et al., 2022)
Microwave-assisted pyrolysis	Rice husk, straw husk and corn husk	2025	Temperatures (700, 750, 800, 850 and 900 °C), microwave powers (400, 450, 500, 550 and 600 W) and dwell times (60, 90, 120, 150 and 180 minutes)	Biochar yields for peanut shells, rice husks, and corn stover ranged from 30.76–43.28%, 25.71–38.93%, and 23.71–36.95% by weight, respectively. As the pyrolysis temperature, microwave power, and/or residence time increased, the biochar yield gradually decreased and eventually stabilised.	(Qiu, Li, Zhao, Naz, & Zhang, 2025)
Fast pyrolysis	Larch tree	2021	600 °C, 2 seconds	The saccharide production of two-component mixtures has been significantly reduced. In the presence of cellulose, the formation of phenolic compounds from lignin has been inhibited by 62%.	(Usino, Ylitervo, Moreno, Sipponen, & Richards, 2021)
Co-pyrolysis	Bamboo and oak wood with plastics (polypropylene [PP] and polystyrene [PS])	2022	Fixed-bed reactor, reaction temperature varied between 723 and 798 K.	The highest HHV of 28.22 MJ/kg was obtained for the oil produced from the co-pyrolysis of bamboo/PS. Furthermore, it was observed that the co-pyrolysis coals possessed high HHVs in the range of 30.73–32.41 MJ/kg. This indicates that they can be used as solid fuels.	(Vo et al., 2022)
Co-pyrolysis	Coal and biomass	2023	Quartz tube fixed-bed reactor, 450 °C, 500 °C, 550 °C, 600 °C, 650 °C, and 700 °C, with coal/biomass mixture ratios of 4:0, 3:1, 1:1, 1:3, and 0:4.	Maximum pyrolysis oil production was achieved under conditions of a raw material ratio of coal to biomass of 3:1 and a pyrolysis temperature of 500 °C. When the ratio of coal to biomass raw materials was 1:3, the quality of the pyrolysis gas was better.	(B. Wang et al., 2023)

Hydrothermal liquefaction

Hydrothermal liquefaction offers a direct route to biomass utilization without drying, eliminating the energy and cost costs required for drying. Utilization of all biomass components can be achieved with this technology and subsequent processes (Hao et al., 2023). Studies using different types of hydrothermal liquefaction are available in the literature. Compared to traditional isothermal hydrothermal liquefaction, fast hydrothermal liquefaction uses a rapid heating process to prevent undesirable secondary reactions and achieves higher biofuel yields in short reaction times. Fast hydrothermal liquefaction has recently attracted the attention of researchers (Ni et al., 2022).

In recent years, microwave-assisted hydrothermal liquefaction has been one of the most studied methods, and a gap in this area was identified in an article by Zhuang et al. In the same article, researchers conducted a study using microwave-assisted hydrothermal liquefaction and demonstrated that microwave radiation facilitated the liquefaction process, resulting in approximately 39.8–43.9% improvement in yield, 3.9–4.0% in calorific value, and 46.6–59.0% improvement in energy recovery efficiency compared to biopulp obtained from conventional liquefaction under similar conditions (Zhuang, Liu, Wang, Zhang, & Ma, 2022).

In a study where catalyst and solvent were used together and their effects on the hydrothermal liquefaction process were investigated, it was concluded that the maximum yields of bio-oil and biochar were 65.0% and 32.0%, respectively, and the calorific values of bio-oil and biochar were 31.2 MJ/kg and 26.5 MJ/kg, respectively. The study also evaluated that alkali catalysts and 1.4-butanediol-triethanolamine mixed solvent could be useful in bioenergy production (X. Zhou, Zhao, Chen, Zhao, & Wu, 2022).

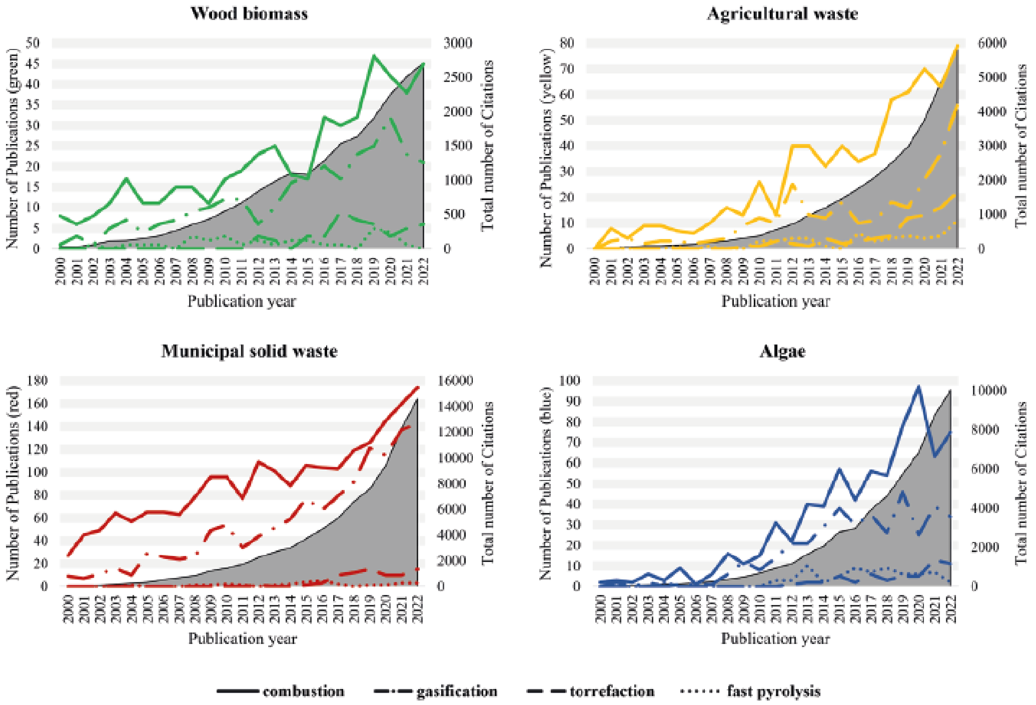
In another study on hydrothermal liquefaction, a two-stage process was applied, first involving a subcritical water reaction followed by a supercritical water reaction. This demonstrated that a greater amount of bio-oil was obtained compared to processing biomass directly with supercritical water. The highest bio-oil yield obtained with the two-stage process was achieved at a was 25.44% by weight in the experiment conducted at a 1:10 biomass/water ratio, and this process was obtained from a subcritical water reaction lasting 30 minutes at 250°C, followed by a second supercritical water reaction lasting 60 minutes at 400°C [37]. When new studies are examined in the literature, it is seen that catalytic hydrothermal liquefaction (Baloch et al., 2021), (Durak, Genel, & Genel, 2026), (Divyabharathi, Subramanian, & Kamaraj, 2025), co-hydrothermal liquefaction (Biswas et al., 2022), (Rawat et al., 2023), (Hongthong, Raikova, Leese, & Chuck, 2020), (Mukundan et al., 2022), (Eladnani et al., 2023) and hydrothermal liquefaction methods using nanoparticles as catalysts (Zhu, Zhao, Tian, Zhang, & Wei, 2022), (Ding, Mahadevan Subramanya, Wang, & Savage, 2023), (Jena, Eboibi, & Das, 2022) are used. This indicates that there is a search for new methods rather than traditional hydrothermal liquefaction processes.

Combustion

Combustion is regarded as a heat-generating process in which the carbon and nitrogen in the biomass react with oxygen in the air. This technique is the oldest, simplest, and most common method used to produce heat and electricity from biomass. The energy content or calorific value of biomass is an important factor and functions as the heat released during combustion under certain conditions (Tekin, Karagöz, & Bektaş, 2014). The biomass combustion method is an ancient and widely used method (Tshikovhi & Motaung, 2023). The fact that the combustion process can be used for all types of biomass provides the greatest benefit. However, combustion is only possible with moisture content below 50% (Tripathi, Sahu, & Ganesan, 2016). A researcher investigating the number of publications and citations between 2000 and 2022 obtained the following graph for thermochemical conversion technologies (Svedovs, Dzikevics, & Kirsanovs, 2023).

Figure 5

Comparison of the number of publications and citations on thermochemical conversion technologies according to biomass type (Svedovs et al., 2023)



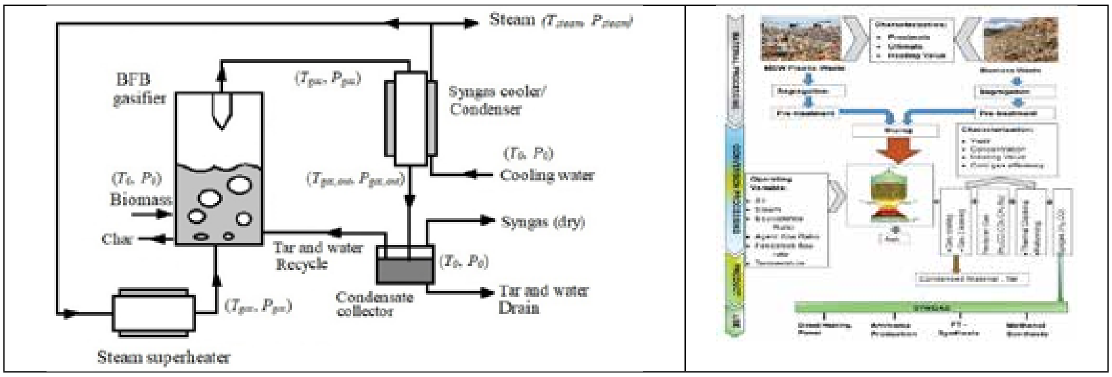
When examining the graphs in **Figure 5**, it is observed that the number of studies and citations on the combustion method has increased more consistently compared to other methods. In addition to traditional combustion methods, there are also studies that integrate new technologies. A study conducted in 2024 mentioned that it is difficult to monitor biomass during its combustion in boilers due to its non-homogeneity, and an online monitoring method was proposed as a solution. The study stated that optical identification allows for the instantaneous and efficient measurement of multiple parameters and that the number of studies in this field is increasing (Yan et al., 2024). Another method is co-combustion. This method involves the simultaneous combustion of multiple biomasses. This method has also been frequently studied by researchers (Xia, Zhang, Tang, & Pan, 2023), (Fan et al., 2024), (Liu et al., 2024).

Gasification

In the gasification process, waste is indirectly converted into fuel or synthetic gases in the presence of oxidants. Part of the fuel is burned to produce heat energy, resulting in hot fuel gases with low heat value (Banu, Sharmila, Ushani, Amudha, & Kumar, 2020). Gasification is a widely preferred method among thermochemical conversion processes and has been extensively studied (Verma et al., 2023). A diagram of co-gasification and steam-based methods, which are subcategories of gasification methods, is shown in **Figure 6**. The products obtained at the end of gasification are also shown here. Various gasification methods have been studied in the literature. These include methods involving a gasification agent (W. Zhang et al., 2025), (Marzoughi, Samimi, & Rahimpour, 2022), (Mojaver, Khalilarya, Chitsaz, & Jafarmadar, 2024), gasification with steam and CO_2 (Castro, Leaver, & Pang, 2026), (S. Zhang et al., 2022), (Hejazi, 2022) gasification with supercritical water (Panichkittikul, Mariyappan, Wu, & Patcharavorachot, 2024) and co-gasification (Khumalo & Patel, 2025), (Xiao, Wang, Cai, Zhang, & Yu, 2024). **Figure 6** shows a schematic representation of the steam gasification method, the steps of the gasification process, and the resulting products.

Figure 6

a) Steam gasification (Hejazi, 2022), b) Steps of the co-gasification process and resulting products (Khumalo & Patel, 2025)



Torrefaction

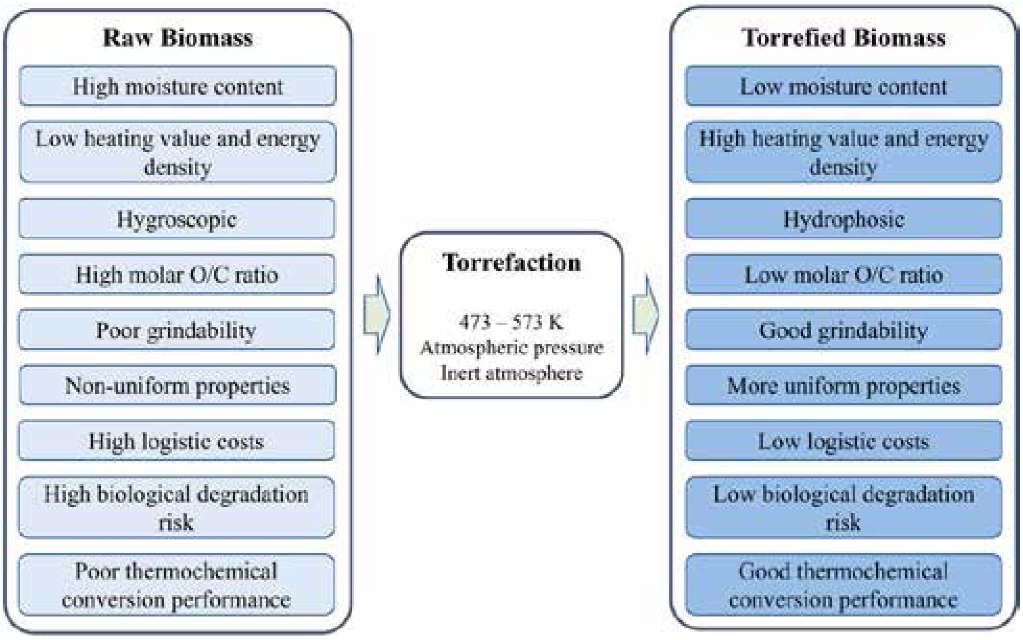
Torrefaction is an extremely important pre-treatment technology for thermochemical applications such as pyrolysis, gasification and liquefaction, and is one of the current topics in the field of renewable energy (Devaraja, Dissanayake, Gunarathne, & Chen, 2022). Pre-treatment techniques such as drying, concentration and roasting aim to improve biomass properties and eliminate some of the problems encountered during conversion. Thermal decomposition at 473–573 K, technically referred to as roasting, significantly improves the properties of biomass. At this temperature range, biomass releases most of its moisture content and a small portion of its volatile matter (Soria-Verdugo, Cano-Pleite, Panahi, & Ghoniem, 2022).

Torrefaction is a mild pyrolysis process that occurs between 473 and 573 K during a holding period of several minutes to an hour, resulting in partial devolatilization of 0–60% by weight of the original dry raw material. During roasting, the release of volatile substances is combined with other changes in physical and chemical structure. The resulting new solid has a higher specific energy density, greater resistance to degradation, and lower milling energy requirements (Bates & Ghoniem, 2014). Torrefacted biomass is essentially hydrophobic. Its hydrophobicity facilitates its handling and processing, particularly by reducing logistics costs (Yantao Yang et al., 2023).

Figure 7 shows the effects of the torrefaction process on biomass. Examining the diagram in **Figure 7**, the differences in properties between raw and torrefaction biomass, as well as the parameters that demonstrate the positive impact of this process on biomass, are clearly visible. The most important of these parameters are moisture content, high calorific value and energy density, low O/C ratio, and improved thermochemical conversion properties.

Figure 7

Effects of torrefaction on biomass (Yantao Yang et al., 2023)



Biochemical Conversion Methods

The biochemical degradation of plant-based biomass (lignocellulosic) is a rather challenging process due to the complex structure of plants. Lignocellulosic biomass typically has a composition of 40–80% cellulose, 15–30% hemicellulose, and 10–25% lignin, with varying suitability for biological conversion. Biochemical methods such as fermentation and anaerobic digestion utilise the various metabolic effects of microorganisms to break down the organic components of biomass into a range of valuable products. A 2022 study revealed that bioethanol and biogas are the most commercially viable products obtained from the biochemical conversion of biomass (Hakeem et al., 2023). Biochemical methods involve the use of microorganisms, enzymes, and genetically modified organisms to convert biomass into fuel (Poornima et al., 2024).

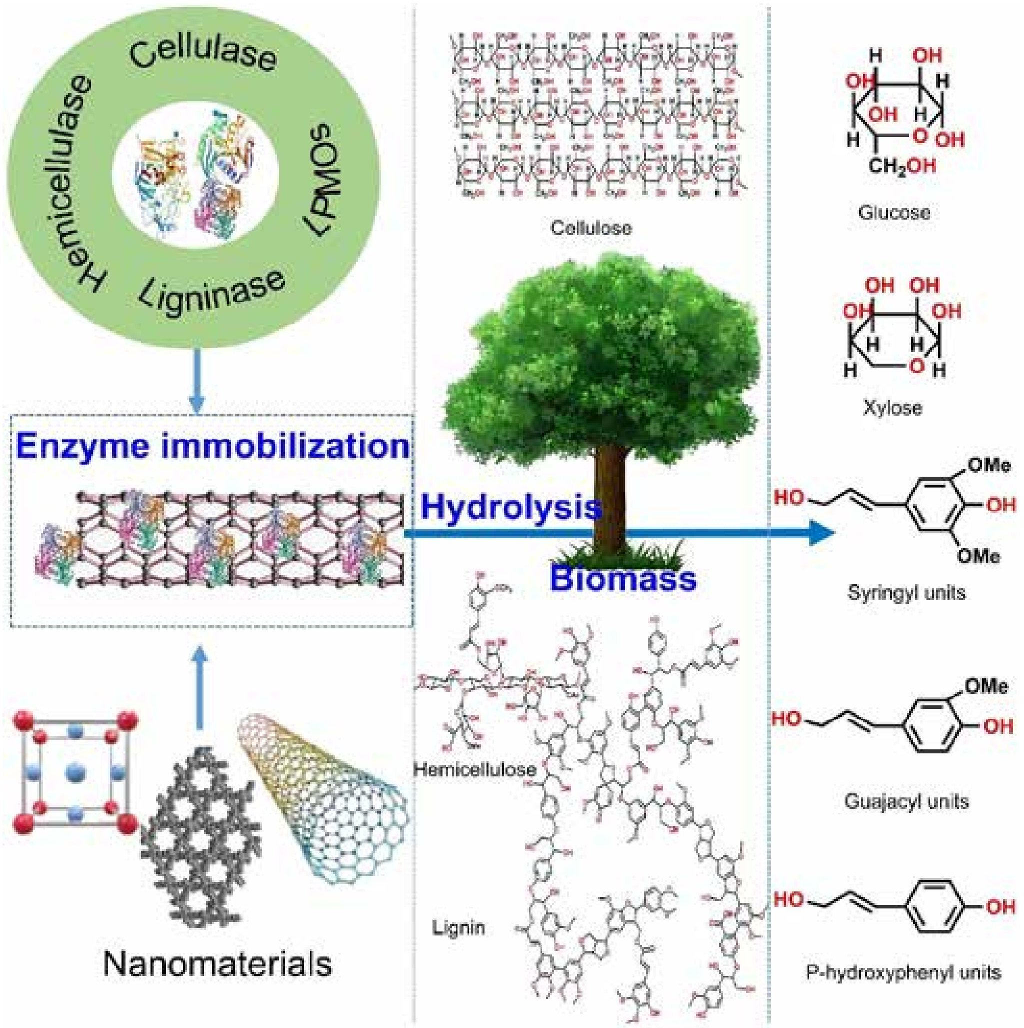
Hydrolysis

Biomass hydrolysis technologies, including acid and enzymatic hydrolysis, are applied to break down feedstock into simple sugars (Tshikovhi & Motaung, 2023). Concentrated acid hydrolysis is often performed by first adding 70–77% sulphuric acid ($H_2SO_4H_2SO_4$)

to break intra- and interchain hydrogen bonds in the biomass, then adding water to dilute the acid to 20–30% and release fermentable sugars (N. Zhou, Zhang, Wu, Gong, & Wang, 2011). Hydrolysis, especially enzyme hydrolysis, is an important process in the conversion of biomass to energy. In the context of biorefining, this process generally involves the decomposition of biomass components into their constituents by using reagents such as enzymes or acids. Examples include the decomposition of polysaccharides into sugars or proteins into amino acids (Wongsirichot, 2024). Hydrolysis has always been a topic of interest for researchers. In recent years, hydrolysis technology has improved, and methods that are more efficient have been investigated. Among these, as seen in **Figure 8**, the studies in which nanoparticles were used (Kotwal, Pathania, Singh, Din Sheikh, & Kothari, 2024), (Luo et al., 2022), (Y. Chen et al., 2021) and pretreatment techniques were applied before the hydrolysis stage (Fu et al., 2021), (Yang Yang, Zhang, Zhao, & Wang, 2023), (Zheng et al., 2022) stand out.

Figure 8

Usage of nanomaterials in hydrolysis method (Luo et al., 2022)



Transesterification

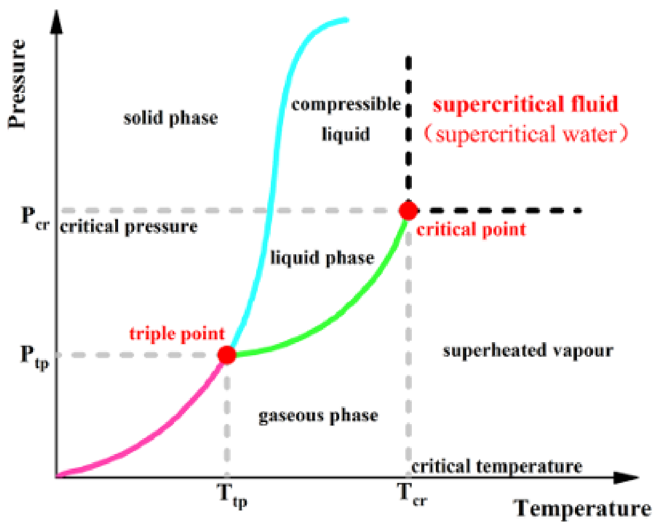
Transesterification involves a series of reversible reactions in which lipids/triglycerides react with alcohol (most commonly methanol), yielding glycerol, monoglycerides, diglycerides, and fatty acid methyl esters—the components of biodiesel—at each step (Tshikovhi & Motaung, 2023). Transesterification is the most popular and cost-effective method of biodiesel production, utilising an acid, an alkali, or an enzyme as a catalyst. Here, triglycerides and primary alcohol are combined in the presence of a catalyst [81]. Lipase, one of the enzymes, exhibits enhanced stability, specificity, enantioselectivity, catalytic effect, and site selectivity. Therefore, it is more suitable for the enzymatic transesterification process in biodiesel production (Aybastier & Demir, 2010). When new studies in the literature are examined, it is seen that transesterification is a technique mostly used in biodiesel studies, applied to various biomasses (Sallet et al., 2025), (Singh, Kumar, Goyal, & Moholkar, 2022), (Bed, Kumar, & RaviKumar, 2025).

Supercritical water

The most abundant substance on Earth is water, which exists in three different phases in nature: solid (ice), liquid, and vapour. Water is found in a supercritical state at a pressure of 22.07 MPa and a temperature higher than 373.9 °C around hydrothermal vents on the sea floor. Water in this state is supercritical water (Z. Chen et al., 2023). **Figure 9** shows the critical regions of water (Q. Wang et al., 2023).

Figure 9

Critical point properties of water (Q. Wang et al., 2023)



Supercritical water gasification effectively converts biomass into gaseous products using water as the reaction medium. This method does not require drying of the feedstock. Thus, in addition to wet biomass such as microalgae and lignocellulosic, wet organic waste products with high moisture content such as sewage sludge and animal manure can also be converted (Dutzi, Boukis, & Sauer, 2023). Supercritical water gasification of biomass in various reactors, such as tubular, batch, and continuous stirred tank reactors, has been widely investigated in recent decades. The walls of these reactors are made of stainless steel or nickel-based alloys, which mostly play a catalytic role in the biomass processing (C. Wang, Zhu, Huang, Jin, & Lian, 2022).

Conclusion

In parallel with the growing world population, energy consumption is also increasing. With this rising consumption, serious damage is being caused to the environment, and plans are being made to increase the share of alternative energy sources, with incentives being provided in this direction. Among these alternative energy sources, biomass energy stands out due to its unique advantages, such as being sustainable and carbon neutral. The intensity of studies in the literature indicates that there are many different methods and techniques for converting biomass into energy. This study focuses on current research into biomass energy conversion methods, particularly thermochemical and biochemical conversion methods.

Recent studies have highlighted that advances in thermochemical and biochemical conversion methods for biomass have led to significant progress in both fundamental science and applied process development. The review found that there have been notable advances in thermochemical approaches (pyrolysis, gasification, hydrothermal processes), developments in catalyst technologies, the use of nanomaterials, and process integration studies. In biochemical conversion methods, the effectiveness of pre-treatment methods, enzymes and the use of nanomaterials has been observed to increase the production efficiency of biofuels. In addition, studies using multiple methods together (hybrid) demonstrate efforts to develop new and innovative methods.

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Current Studies on Lupinus Species Growing in Türkiye

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Introduction

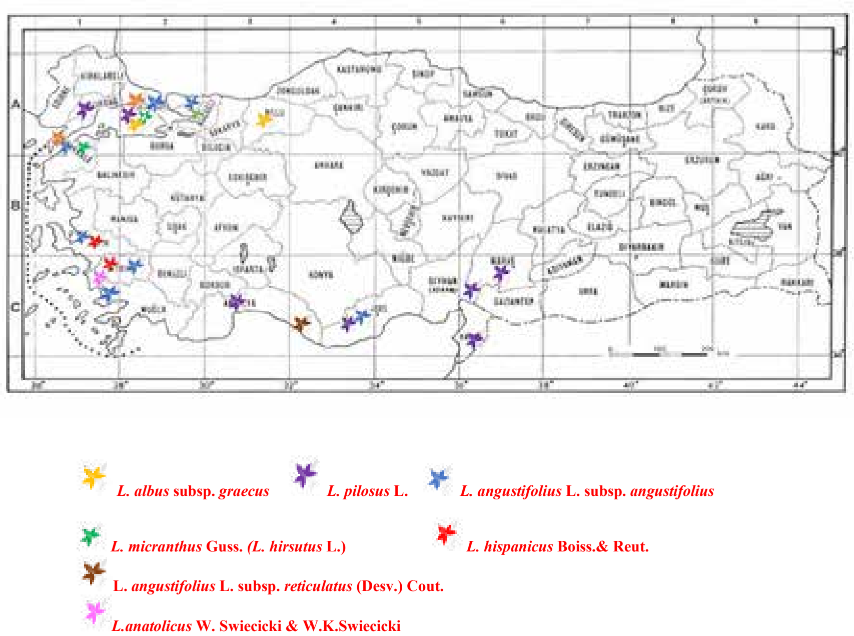
Lupinus L. species (lupin or lupine, Fabaceae family) are wild or cultivated in the Mediterranean, South Aegean and Marmara regions of Turkey and it has been reported in the literature that it is an annual herbaceous plant with thick, hard and bitter seeds (Akbar, 2020; Davis, 1984; Davis et al., 2008; Gross et al., 1976; Güner & Aslan, 2012). The general characteristics of the *Lupinus* genus can be given as follows: annual, hirsute herbaceous; leaves digitate; stipules adnate to the base of the petiole, setaceous; inflorescence racemose, the flowers alternate or verticillate; calyx bilabiate, 4-5-toothed, bracteoles usually persistent, attached to base of calyx; corolla with an obtuse keel; stamens monadelphous; legume a terete, 2-6-seeded, usually hirsute hairy, usually in non calceous soils (Davis, 1984; Davis et al., 2008; Drummond et al., 2012; Mirza et al., 2023).

The *Lupinus* L. plant has nearly 300 species in various countries, besides six species growing in Turkey. Gene banks have been established in different European and Australian countries (https://www.igr.poznan.pl/uploads/resources/Linki%20WS/Lupinus_Collections_Database.pdf; https://www.planthealthaustralia.com.au/wp-content/uploads/2024/01/10-124.pdf) (Swiecicki et al., 2000)

Nine taxa are *Lupinus albus (*white lupine, termiye*)*, *L. albus* subsp. *albus* (Egyptian lupine, Syn: *L. termis* ,termiye), *L. albus* subsp. *graecus* (Syn: *L. graceus*, tavşan baklası), *Lupinus angustifolius* (blue lupine, acı bakla*)*, *L. angustifolius* subsp. *angustifolius* (Syn: *L. leucospermus*, acıbakla) *Lupinus micranthus* (Syn: *L. hirsutus*, pilous lupine, domuz baklası), *Lupinus hispanicus* (Syn: *L.rothmaleri*, delice bakla), *L. pilosus* (Syn: *Lupinus varius*, gavur baklası) and the endemic *Lupinus anatolicus* (mısır baklası) growing in coastal cities in Turkey (Bedevian, 1936; Davis, 1984; Davis et al., 2008; Drummond et al., 2012; Güner & Aslan, 2012). (Figure 1).

Figure 1

Distribution of Lupinus species in Turkey



Among the *Lupinus* species cultivated for medicinal purposes, "Termiye", popularly known as the seed of lupine, has been reported to have strengthening and antihelminthic effects on urinary tract diseases, removal of kidney stones and sand, and also to relieve rheumatism, nerve pain, and headache when boiled in water and consumed. It is known that termiye is consumed as a coffee in diabetic patients in the Konya region (Baytop, 1997, 2021; Tuzlacı, 2011). It is frequently used in floury foods and meat products, as well as in the composition of gluten-free biscuits and bakery products (Leonard et al., 2019; Maghaydah et al., 2013) https://www.fao.org/4/y5019e/y5019e07.htm. Additionally, products containing lupin seeds are sold in cosmetic stores and are also manufactured in various laboratories. (Lupaline®, CO2llageneer®, ACTIMP® Bio) (Caramona et al., 2024)**.**

It is known that *Lupinus* L. was used in Dioscorides' "De Materia Medica" and a work of Hippocrates against inflamed areas and birthmarks or for cosmetic purposes, respectively

(Kurlovich, 2002; Osbaldeston & Wood, 2000). In the Unani system, *Lupinus* species were used for wound healing and anthelmintic purposes. Several scientific studies, both *in vivo and in vitro*, support this finding (Akbar, 2020; Dubois et al., 2019; Prusinski, 2017). Numerous studies on the use of lupin seeds in animal and human diets have shown that they can compete with soybean seeds. Lupine seeds contain about 50% protein, up to 13% fat, and numerous bioactive compounds (Król et al., 2018; Wäsche et al., 2001).

In many countries, including Türkiye, especially in Asia and Europe, the nutritional value (niacin, riboflavin, thiamine) in the production of fermented products (pastry, crisps, bread, and emulsified meat, etc.) is very high in the Lupinus seeds (Erbaş et al., 2005). The antimicrobial effect of dichloromethane extracts of some *Lupinus* species against *Pseudomonas aeruginosa, Klebsiella pneumoniae, B. subtilis,* and *S. aureus* strains was determined (Erdemoglu et al., 2007; Romeo et al., 2018).

There are studies on seed pods of some *L. angustifolius* and *L. albus* cultures, and various extracts prepared from them induced apoptosis in MIA PaCa-2 (human pancreatic carcinoma) (Ishaq et al., 2022). In addition, *L. albus* seeds are known to have hypolipidemic, antiepileptic, and antihelminthic (Vollmannova et al., 2021), antihypertensive (HunieTesfa et al., 2025), and antidiabetic (Aydın et al.,2021), anti-inflammatory (Pereira et al., 2022)**,** and antifungal (Caramona et al., 2024) effects.

Some *Lupinus* wild or cultivated species (*L. albus* and *L. angustifolius*) have been reported to show antioxidant activity (Karamać et al., 2018; Król et al., 2018; Siger et al., 2012)Cammilleri et al.,2024). The species of this plant contains many different primary and secondary metabolites. It is known that its seeds contain a significant amount of phenolic compounds (phenolic acids, flavonoids, isoflavonoids), polyphenols, carotenoids, phytosterols, tocopherols, and are rich in fatty acids (oleic and linoleic acids, etc.) (Ishaq et al., 2022; Yorgancılar et al., 2018)(Özyazıcı.,2022). The above-ground parts of some species (*L. albus, L. angustifolius*) of various genotypes contain alkaloids, including 13-tigloyloxylupanine, lupanine (Chludil et al., 2009). *Lupinus* species have hepatotoxic and teratogenic effects due to quinolizidine alkaloids **(**angustifoline, sparteine(lupinidine), lupinine**)** and piperidine alkaloids (anagyrine, ammodendrine) (Patočka and Ho,2008).

In this chapter, botanical characteristics, traditional uses, chemical composition, bioactivity, and clinical studies of wild or ecotype/genotype *Lupinus* species growing in Turkey, as well as their herbal drugs and side effects, are reported. Also, scientific studies conducted in other countries on these species growing in Türkiye are reviewed.

Ethnic uses of *Lupinus* species in Türkiye

While *L. varius* is used as an ornamental plant, *L. albus* is used as a tonic, cardioactive, and diuretic, as well as in various skin diseases. Its seeds are used as anthelmintics and antidiabetics in the Marmara and Aegean Regions of Turkey, besides in Europe and the Balkans due to their high protein, polysaccharides, and low starch content. *L. luteus* (yellow lupin) is used in the Mediterranean region as a blood pressure-lowering agent, in cardiovascular diseases, and against colon cancer (Ishaq et al., 2022; Khan et al., 2015).

In Konya City and its surrounding provinces, the seeds of lupine, whose bitterness has been removed, are consumed as snacks and used in animal nutrition. Additionally, the stem is preferred as a fertilizer and fodder. *Lupinus angustifolius* seeds are used for the control of obesity and cholesterol in various countries, particularly in Europe, New Zealand, and Australia (Ishaq et al., 2022). The external use of maceration prepared from its sprouts protects ruminants from lice and fleas (Yaşar et al. 2015). Lupin species naturally contain alkaloids, some of which can be bitter and toxic. For this reason, soaking or boiling the seeds in water to remove the bitterness has often been practiced colloquially in traditional medicine (Baltacıoğlu & Özcan Tarım, 2024). Protein powders preferred by vegans are also frequently used. Links to these are provided below;

Patagonia Proteins – Lupine Protein Powder (Andes Cocoa) (https://patagoniaproteins.com/products/lupine-protein-powder-andes-cocoa-2-2-lb)

Raab Vitalfood

(https://www.naturitas.us/p/supplements/sport/proteins/organic-lupine-protein-powder-500-g-of-powder-raab)

Tarwi – Pure Lupin Protein (300g)

(https://tarwi.co/products/protein)

Mikuna – Chocho Lupin Protein Powder

(https://mikunafoods.com)

Pure Inka Foods – Lupin Protein Powder (55% Protein)

(https://cerebro.faire.com/product/p_hvtkzs6dru)

Trace element ingredients and nutritional value of Turkish native *Lupinus* sp.

In a study conducted in Turkey by Yorgancılar et al. (2018), the mineral and physical properties of white lupin (*Lupinus albus* L.) seeds were determined. The study revealed the following concentrations of minerals: phosphorus (0.14%), potassium (0.4%), calcium (0.04%), magnesium (0.06%), iron (11.9 ppm), manganese (533.4 ppm), and zinc (15.8 ppm) (Yorgancılar et al., 2018).

A comparison of the results with those obtained in studies conducted in different countries suggests that the levels of certain nutrients are lower. For instance, in the extant literature, phosphorus has been reported as ranging from 0.43% to 0.72% in white lupins, potassium as ranging from 0.86% to 1.11%, magnesium as ranging from 0.12% to 0.22%, and manganese as ranging from approximately 896 mg/kg (Pereira et al., 2022; Straková et al., 2006). In the Turkish sample, these values were found to be lower, especially for phosphorus, potassium, and magnesium. In general, white lupins cultivated in Turkey exhibit comparable oil and protein content to international data, yet demonstrate lower mineral values. These differences underscore the impact of genotype, soil structure, climate, and cultivation techniques on nutrient content.

In studies conducted on the nutritional value of four different cultures obtained from *L. agustifolius* seeds found in Poland, total oligosaccharides were determined to be 80-97 g/100g, crude protein (79.4-82.3 g/kg), and amino acids lysine (1.7) and methionine (2.7) were found (Kaczmarek et al., 2014).

The highest protein content was found in the lupin varieties belonging to *L. luteus* (ca. 465 g/kg), followed by *L. albus* (ca. 360 g/kg) and *L. angustifolius* (ca. 330 g/kg) (Sujak et al., 2006). In the literature, it is noted that cookies can be produced successfully with lupin flour (Baltacıoğlu & Özcan Tarım, 2024; Obeidat et al., 2013).

Some primary and secondary metabolites of *Lupinus* species in Türkiye

In addition to the important nutritional compounds mentioned above, some *Lupinus* species also contain anti-nutritional compounds (quinolizidine alkaloids) (Sujak et al., 2006). Important main alkaloids found in the literature related to some *Lupinus* species growing in Türkiye are summarized in Table 1. Also, flavonoids (apigenin and luteolin derivatives) were detected in different *Lupinus* species (Czubinski et al., 2019; Vollmannova et al., 2021).

Table 1

Some Important Alkaloids and Other Metabolites in Lupinus Species in Türkiye

PLANT NAME	LOCATION	USED PARTS	ACTIVE COMPOUNDS
Lupinus albus	East Marmara, West Black Sea (Türkiye)	stem, seed, leaf	Lupanine 13-Hidroksilupanine Albine Multiflorine α- isolupanine]

Lupinus angustifolius	Çatalca-Kocaeli in the Marmara Region, the Egean Region, Antalya and Adana	stem, seed, leaf	Apigenin 4-Hydroxybenzoic acid 4-hydroxycinnamic acid Gallic acid protocatechuic acid, caffeic acid *p*-coumaric acid, genistein
Lupinus hispanicus	Aegean Region	seed leaf stem root	Lupinine Gramine
Lupinus micranthus	Çatalca-Kocaeli in Marmara, East Marmara Region	seed leaf stem root	Albine Lupanine Multiflorine 13-α hydrokxylupanine 13-α- hydroxymultiflorine 13- angeloxymultiflorine

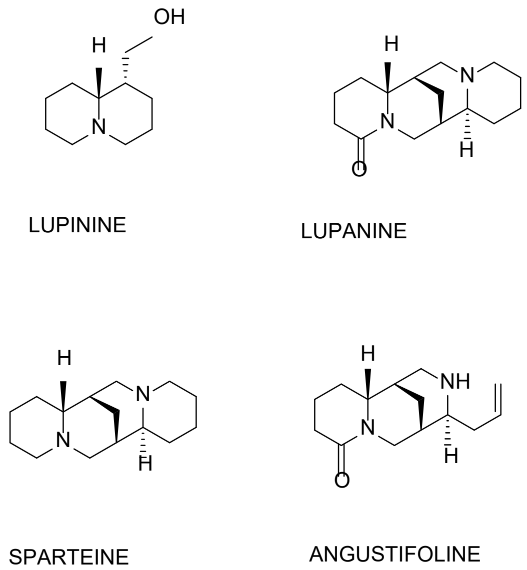
*(References: (El-Adawy et al., 2001; Khan et al., 2015; Maknickienė & Asakavičiūtė, 2008; Martínez-Villaluenga et al., 2009; Pastor-Cavada et al., 2009; Petterson, 2000; Pilegaard, Kirsten; Gry, 2008; Porres et al., 2007; Ruiz-López et al., 2019; Siger et al., 2012; Sujak et al., 2006) Christiansen ve ark. (1997),

It has been reported that the total QA level in Turkish-origin bitter *L. albus* populations is approximately 12–19 g/kg dry matter, with this amount being largely (80–87%) derived from the lupanine alkaloid (Awad-Allah & Elkatry, 2013; Muzquiz et al., 2011; Pilegaard, Kirsten; Gry, 2008). International data indicate that the total QA content in bitter *L. albus* genotypes generally ranges from 4–10 g/kg, reaching up to 11% in some wild accessions, while in sweet lines, it is kept below 200 mg/kg to be suitable for food use ('Outcome of a Public Consultation on the Draft Scientific Opinion on the Risks for Animal and Human Health Related to the Presence of Quinolizidine Alkaloids in Feed and Food, in Particular in Lupins and Lupin-derived Products', 2019; Michael Wink et al., 1995). Wild types may reach levels of up to 2.0%, posing toxicity risks (Kamel et al., 2016). Among the various *Lupinus* species cultivated in Turkey, *L. albus* has received the most extensive study, with research focusing on the total quinolizidine alkaloid (QA) levels present in local 'bitter' genotypes. These levels are consistent with the existing data concerning bitter species on an international scale. Despite the absence of direct quantitative data on *L. angustifolius* and *L. luteus* in Turkey, recent studies have indicated that these species contain QA levels of 13–16 g/kg and 4–13 g/kg, respectively, in bitter genotypes. Conversely, in sweet lines, breeding efforts have successfully reduced these levels to below 0.01% (~100 mg/kg) through selective breeding (Bähr et al., 2014; Cowling & Gladstones, 2000). A study on *Lupinus angustifolius* cultivated in Turkey identified 13a-hydroxylupanine and lupanine as the most significant alkaloids, accounting for around 50.78% and 23.55% of the total alkaloid content, respectively (Erdemoglu et al., 2007). Alkaloid profiles are species-specific; lupanine and 13-hydroxy-lupanine have been identified as predominant in *L. albus* and *L. angustifolius*, while sparteine and lupanine have been found in high concentrations in *L. luteus* (Boschin & Resta, 2013; Frick et al., 2017). Genetic factors and environmental conditions, such as temperature, soil pH, and cultivation practices, influence the variation in alkaloid content of *Lupinus* sp.. Research showed that soil pH significantly affects alkaloid concentration. Higher alkaloid contents are found in environments with a lower pH (Jansen et al., 2012). It is a fact that abiotic stresses, such as drought and elevated temperatures, lead to increased alkaloid synthesis in *Lupinus* species, including specific cultivars such as *Lupinus angustifolius* (Święcicki et al., 2019; Valente et al., 2024). The formula of alkaloids has been given in Figure 2.

In a study, Jansen et al. definitively noted that the alkaloid content decreases significantly at higher pH levels. This clearly suggests that careful management of soil conditions could optimise alkaloid profiles for the desired outcomes (Jansen et al., 2012). For instance, *Lupinus albus* and *Lupinus angustifolius* are categorised as edible varieties with lower toxicity, while many wild types contain alkaloids that are highly relevant to animal and human health (Hassine et al., 2021). For instance, *Lupinus mutabilis* has been identified as a species of particular interest due to its high alkaloid levels, which possess both therapeutic potential and the potential for toxicity if not properly processed (Cortés-Avendaño et al., 2020).

Figure 2

Some Alkaloids in Lupinus Species



Research on bittering methods (soaking, boiling, and ultrasound, etc.) conducted in Türkiye has shown that these processes significantly reduce QA levels in seeds, making them compliant with international standards for food use (Baltacıoğlu & Özcan Tarım, 2024; Chamone et al., 2023; Erbas, 2010)**.** However, it has been reported that QA levels can vary significantly depending on factors such as genotype, growing conditions, plant organ, and analysis method (Bähr et al., 2014; Chamone et al., 2023; Frick et al., 2018; Jansen et al., 2012; Kamel et al., 2016; Muzquiz et al., 2011; Valente et al., 2024). This comparison reveals that the alkaloid levels of *Lupinus* species in Turkey are similar to global variation ranges, but that local genotypes are predominantly of the high-alkaloid 'bitter' form. Consequently, the development of sweet species for food and feed purposes, whilst concomitantly reducing the alkaloid levels of existing bitter genotypes by the effective use of processing methodologies, will constitute a pivotal strategy to increase the agricultural and industrial potential of *Lupinus* in Türkiye. Also, for the extraction of lupin alkaloids (such as Lupanin-type quinolizidine alkaloids), solid-phase extraction methods are utilized, or extraction processes are performed in acidic or basic environments using various apolar or polar solvents (such as methanol-water mixtures**)** (Erdemoglu et al., 2007; Karamać et al., 2018; Muzquiz et al., 2011)**.**

White lupin (Lupinus albus L.) seeds are notable for their high protein content, ranging from approximately 32–48% on a dry weight basis (Dervas et al., 1999; Prusinski, 2017). Approximately 80–90% of lupin proteins consist of the globulin fraction, with the remaining portion comprising albumins and other small protein fractions (Duranti et al., 2008). Among globulins, there are subclasses of α-conglutin (11S), β-conglutin (7S), γ-conglutin (10S), and δ-conglutin (2S), and they are evaluated as functional components in the food industry due to their technological properties (Lam et al., 2018). When evaluated in terms of amino acid profile, white lupin proteins are particularly rich in lysine and also contain high amounts of essential amino acids such as leucine and threonine(Sujak et al., 2006). However, the levels of sulfur-containing amino acids, methionine and cysteine, are relatively low (Prusinski, 2017). These characteristics enhance the potential use of white lupin as both a high-nutritional-value plant protein source and a valuable component in gluten-free food formulations. Nowadays, the extraction of concentrates, isolates, and hydrolysates from lupin seeds is commonly due to their easy digestibility and content of important bioactive peptides. The extraction methods generally used for these protein-based products include alkaline neutral extraction, isoelectric precipitation, ultrafiltration, salt extraction, and ultrasonication and microwave-assisted methods (Lemus-Conejo et al., 2023; Rababah et al., 2023).

If we explain other metabolites and their general methods of obtaining from Lupinus species; the oleic acid content (42.37) was high in *L. albus*, a *Lupinus* species grown in Turkey, while the linoleic acid content (54.06) was higher in *L. pilosus*, both of which were collected from Tunisia, Egypt, and some Mediterranean countries (wild/commercial cultivars) and extracted using a Soxhlet apparatus. The Soxhlet apparatus is also used to remove alkaloids from lupin seed flour. High nutritional value amino acids (lysine, conglutin) and up to 45% protein (glutamic acid, aspartic acid, and arginine) have been identified in some lupins (Akremi et al., 2025; Pereira et al., 2022; Rani & Rani, 2025). On the other hand, the presence of saponins in lupine species has been determined using the ultrasound-assisted extraction method (Bitwell et al., 2023). The volatile oil obtained from flowering shoots of *L. varius* by hydrodistillation was analyzed by GC-MS, and 6,10,14-trimethyl-2-pentadecanone (20.5%) was identified as the main component (Al-Qudah, 2013). In addition, various triterpenes (squalene) and the compounds ursolic acid and lupeol were reported to be present in the oil (Pereira et al., 2022). In a study conducted on the genotypes of *Lupinus albus L.* seeds grown in Konya, Turkey, nearly 100 different compounds were detected in the volatile oils obtained by the HS-SPME (Headspace Solid Phase MicroExtraction) method using four different SPME fibers (Şimşek Sezer et al., 2023).

Biological activities of *Lupinus* species from Turkey

A wide range of therapeutic properties has been reported for *Lupinus* species, particularly in studies investigating their pharmacological effects. These effects include antidiabetic, antioxidant, antimicrobial, anti-inflammatory, and anticancer activities. The therapeutic potential of lupin is largely attributed to its rich composition of bioactive compounds, including flavonoids, alkaloids, polyphenols, and peptides. Numerous studies have elucidated the bioactive constituents and molecular mechanisms responsible for these properties, highlighting the therapeutic relevance of lupin in both pharmaceutical and nutraceutical contexts.

Antioxidant Activity

The antioxidant capacity of *Lupinus* species—especially *Lupinus angustifolius* (commonly known as blue lupin) and *Lupinus* albus (white lupin)—has garnered significant attention due to its potential role in therapeutic applications. These species are distinguished by their bioactive richness, notably peptides and polyphenols, which significantly contribute to their antioxidant effects.Studies have highlighted that protein hydrolysates derived from *L. angustifolius* possess considerable antioxidant properties. The bioactive peptides isolated from these hydrolysates have been shown to improve metabolic markers and protect against oxidative stress by increasing the total antioxidant capacity in animal models of metabolic syndrome (Lemus-Conejo et al., 2020; Santos-Sánchez et al., 2021). These peptides mitigate oxidative damage by reducing inflammatory enzymes and activating endogenous antioxidant mechanisms (Cruz-Chamorro et al., 2021; Santos-Sánchez et al., 2022).

The polyphenolic content of *Lupinus* species also plays a central role in their antioxidant potential. In a comparative study evaluating the antioxidant properties of *Lupinus micranthus*, *L. hispanicus*, *L. angustifolius*, *L.luteus*, and *L. hispanicus* demonstrated the highest antioxidant activity, followed by moderate activity in *L. micranthus* and *L. luteus*. *L. angustifolius* exhibited the lowest antioxidant effect among the species tested (PASTOR-CAVADA et al., 2010). Moreover, lupin seeds have been reported to contain high polyphenol concentrations, showing superior antioxidant capacity compared to other legumes (Karamać et al., 2018). Germination has been shown to enhance the phenolic content and radical-scavenging ability of lupin seeds (Dueñas et al., 2009) by the development of extraction techniques that further optimize the isolation and functionality of these compounds (Tesarowicz et al., 2022).

Extracts from *L. albus* seeds increased plasma glucose levels and decreased oxidative stress markers such as malondialdehyde (MDA) in diabetic rats, particularly at a dose of 10 mg/kg (Yildirim et al., 2020). Ethanolic extracts of *L. albus* demonstrated dose-dependent increases in antioxidant enzymes, including catalase (CAT), superoxide dismutase (SOD), glutathione peroxidase (GPx), and glutathione (GSH). Roasting has also been reported to enhance the antioxidant profile of lupin seeds. Although thermal processing may degrade some bioactive constituents, it promotes the formation of melanoidins—compounds with antioxidant capacity due to their metal-chelation properties—thereby enhancing overall antioxidant potential (Al-Amrousi et al., 2022). Peptides in *Lupinus* species are short amino acid sequences produced through the enzymatic hydrolysis of seed storage proteins from the conglutin families (α, β, γ, δ). These peptides are typically released via *in vitro* gastrointestinal digestion or enzymatic treatment using pepsin, trypsin, alcalase, or pancreatin. *In vitro* studies have demonstrated that lupin-derived peptides exert antioxidant effects, inhibit metabolic enzymes such as ACE, α-glucosidase, and DPP-IV, and reduce the production of pro-inflammatory cytokines by modulating the NF-κB and MAPK signaling pathways (Cabello-Hurtado et al., 2016). The ecological adaptability and nutritional profile of *Lupinus* species, including their content of essential amino acids, lipids, and dietary fiber, render them promising components in diets aimed at mitigating chronic disease risks through antioxidant support (Thambiraj et al., 2019; Yildirim et al., 2020). Consequently, lupin is increasingly recognized not only as a valuable agricultural crop but also as a functional food relevant to public health interventions.

In summary, *L. angustifolius* and *L. albus* have demonstrated significant antioxidant properties mediated by their bioactive peptides and polyphenols. The diversity of extraction and preparation methods further emphasizes their potential as functional foods for enhancing resistance to oxidative stress and promoting overall health.

No studies have yet been conducted on the antioxidant properties of *Lupinus anatolicus*, a species native to Turkey.

Anti-inflammatory Effects

The genus *Lupinus* has garnered considerable scientific attention due to its potential anti-inflammatory properties. Extracts obtained from germinated seeds of *Lupinus angustifolius* and *Lupinus albus* have demonstrated moderate anti-inflammatory activity in both *in vitro* and *in vivo* models. These effects are primarily attributed to high levels of flavonoids, phenolic acids, and tocopherols, which become more abundant following germination. The extracts inhibit key pro-inflammatory cytokines such as TNF-α, IL-6, and IL-1β by downregulating the NF-κB signaling pathway. They also suppress the production of prostaglandins and leukotrienes by inhibiting cyclooxygenase-2 (COX-2) and possibly lipoxygenase (LOX) enzymes. *In vivo* studies have reported that *Lupinus* extracts reduce inflammation by mitigating tissue edema, cellular infiltration, and vascular congestion (Andor et al., 2016). Moreover, protein hydrolysates derived from these seeds exhibited similar anti-inflammatory effects in THP-1-derived macrophages. The hydrolysates significantly reduced the production of TNF-α, IL-1β, and IL-6, while increasing levels of the anti-inflammatory chemokine ligand CCL18 (Khan et al., 2015; Millán-Linares et al., 2014). For instance, hydrolysates obtained through enzymatic treatment with alcalase enzyme showed a 45% reduction in TNF-α, 32% reduction in IL-1β, and 43% reduction in IL-6 compared to controls. A separate group treated with alcalase on hydrolysis demonstrated slightly lower inhibition levels. Importantly, CCL18 expression was nearly doubled in cells treated with both hydrolysates. Cruz-Chamorro et al. (2021) further confirmed that lupin protein hydrolysates (LPHs) exert anti-inflammatory effects by inhibiting inflammation-associated enzymes such as phospholipase A2 and COX-2. The study concluded that LPHs significantly attenuated pro-inflammatory cytokine levels in macrophage cultures, underscoring their therapeutic potential.

A systematic review by Castillo et al. (2023) exhibited the potential of *Lupinus albus* constituents in regulating lipid metabolism, which may, in turn, influence inflammatory pathways involved in metabolic disorders. Similarly, Lima-Cabello et al. (2020) identified specific proteins in *L. angustifolius*, particularly γ-conglutin, with promising anti-inflammatory properties. These proteins reduced oxidative stress and inflammation markers in pancreatic cell lines, suggesting a dual role in both nutrition and inflammation. The anti-inflammatory activity of lupin is closely associated with its phenolic content. For example, Danciu et al. (2017) quantified the total phenolic content in lupin seeds and linked it directly to both antioxidant and anti-inflammatory effects. These phenolic compounds modulate oxidative stress and inflammatory cascades, indicating that lupin-enriched diets may provide protective benefits against chronic inflammatory diseases.

In conclusion, strong evidence supports the anti-inflammatory potential of *Lupinus* species, especially through their rich content of bioactive peptides and phenolic compounds. These effects are mediated by suppression of key inflammatory mediators and modulation of intracellular signaling pathways, indicating the potential of lupin as both a functional food and a therapeutic agent in managing inflammation-related disorders.

Antidiabetic Effects

The pharmacological potential of *Lupinus* species in the management of diabetes has gained considerable interest in recent years. Seeds of *Lupinus albus* and *Lupinus angustifolius* are particularly rich in bioactive compounds responsible for notable hypoglycemic properties, making them promising dietary components for glycemic control and prevention of diabetes-related complications. In Egypt, for instance, *L. albus* seeds have traditionally been used by individuals with type 2 diabetes, although the efficacy of this use is not thoroughly documented (Eskander & Won Jun, 1995; KUBO et al., 2000). One of the primary mechanisms by which lupin exerts antidiabetic effects is through modulation of glucose metabolism. Studies have shown that polysaccharides and peptides derived from lupin seeds significantly reduce blood glucose levels in diabetic models. For example, ethanolic extracts of *L. albus* seeds have been shown to lower plasma glucose concentrations and oxidative stress markers, such as malondialdehyde (MDA), while also increasing antioxidant enzyme activity, including superoxide dismutase (SOD) and catalase, in streptozotocin-induced diabetic rats (Yildirim et al., 2020). The γ-conglutin protein in lupin has been related to insulin-mimetic activity in cellular models, supporting its potential to enhance glucose uptake and regulate insulin signaling (Andor et al., 2016). Additionally, the compounds such as 13-α-hydroxylupanine, lupanine, 17-oxolupanine, 2-thiosparteine, and sparteine have demonstrated the ability to increase insulin secretion *in vitro* (Díaz et al., 1990; M Wink, 2005). Traditional uses of lupin in Turkey support its hypoglycemic reputation. For instance, *L. albus* subsp. *albus*, commonly known as “termiye” or “Jew’s foot,” is consumed in Konya and Tekirdağ regions in various forms (raw, boiled, or decocted) to manage diabetes (Akalın & Akpınar, 1994; Koçoğlu Keklik et al., 1996). Similarly, *L. angustifolius* (referred to as “yahudibaklası” in the İzmir region) is traditionally roasted and consumed with hot water for diabetes patients (Ugulu et al., 2009).

Phenolic compounds in lupin seeds, particularly polyphenols, have been shown to control glycemic index and protect against oxidative stress in diabetic patients (Danciu et al., 2017). Germination of lupin seeds enhances these effects by increasing the bioavailability of polyphenols and other bioactive components (Andor et al., 2016).

In a comparative animal study, *L. albus* extracts were found to reduce hepatic and pancreatic damage caused by diabetes. Rats were divided into five groups: healthy control, diabetic control (streptozotocin-induced), gliclazide-treated, *Hyphaene thebaica*-treated, and *L. albus*-treated. Daily oral administration of 700 mg/kg of *L. albus* significantly alleviated diabetic symptoms and tissue damage (Tohamy et al., 2013). Clinical studies have also demonstrated that dietary interventions using lupin can reduce postprandial glucose levels and improve lipid profiles in humans, reinforcing its role in dietary control for diabetes management (Hodgson et al., 2010). These benefits are further supported by the LDL cholesterol-lowering effects of lupin proteins, which stimulate LDL receptor activity (Sirtori et al., 2004).

Lupin seeds also offer functional properties like high-quality proteins and soluble fibers, which improve satiety and reduce postprandial glycemia. Due to their low glycemic index and ability to delay glucose absorption, lupins are well-suited for individuals with type 2 diabetes (Ward et al., 2020). Oxidative stress, a major contributor to diabetic complications, is mitigated by the antioxidant properties of *Lupinus* species. Peptides and polyphenols reduce oxidative damage and inflammation, thereby lowering the risk of comorbidities such as nephropathy and liver fibrosis (Garmidolova et al., 2022; Sayari et al., 2023). A study using *L. angustifolius* extracts demonstrated that it induces antioxidant enzymes and regulates anti-inflammatory cytokines in diabetic conditions (Millán-Linares et al., 2014)..

In conclusion*, Lupinus* species exhibit strong antidiabetic properties through multiple mechanisms, including regulation of glucose metabolism, insulin-mimetic effects, antioxidant protection, and modulation of inflammation. Their integration into dietary strategies offers promising benefits for the management and prevention of diabetes and its associated complications.

There are currently no published antidiabetic effects of *Lupinus micranthus*, *Lupinus hispanicus*, or *Lupinus anatolicus*.

Antihypertensive Effects

The antihypertensive potential of *Lupinus* species, particularly *Lupinus albus* and *Lupinus angustifolius*, has drawn attention as a natural dietary approach to managing high blood pressure. These species contain a diverse range of phytochemicals, including alkaloids, flavonoids, and peptides, which are known to contribute to cardiovascular health by modulating vasodilation and oxidative stress.

Several studies have demonstrated that *Lupinus* seeds influence the nitric oxide (NO) pathway, a critical regulator of vascular tone. Flavonoids and peptides derived from lupin have been shown to stimulate NO production, thereby promoting vasodilation and lowering systemic blood pressure (Hassine et al., 2021). Additionally, *Lupinus* extracts may modulate the renin-angiotensin system (RAS), a hormonal system that regulates blood pressure and fluid balance. Protein fractions such as β-conglutin isolated from *L.*

angustifolius have been reported to enhance NO synthesis and reduce vascular resistance (Lima-Cabello et al., 2019).

Of particular importance are the bioactive peptides in *Lupinus* species, which exhibit angiotensin-converting enzyme (ACE) inhibitory activity. Inhibition of ACE prevents the conversion of angiotensin I to angiotensin II, a potent vasoconstrictor, thereby contributing to blood pressure reduction. Clinical studies and *in vitro* analyses showed that lupin-based food products lead to a decrease in both systolic and diastolic blood pressure (Castillo et al., 2023; Czubinski & Feder, 2019).

Phenolic compounds in lupin seeds also improve endothelial function by increasing the bioavailability of NO and reducing oxidative stress. This effect supports vascular relaxation and helps maintain arterial elasticity (Czubinski & Feder, 2019; Loredo-Dávila, 2012). Additionally, lupin phenolics have been shown to inhibit calcium influx in vascular smooth muscle cells, further supporting their role in reducing vascular resistance and blood pressure (Czubiński & Feder, 2019).

In summary, *Lupinus* species have antihypertensive activity through multiple mechanisms, including ACE inhibition, enhanced NO signaling, calcium channel modulation, and oxidative stress. These properties support the use of lupin as a functional food ingredient in the strategies of hypertension management.

There are no reported studies investigating the antihypertensive properties of *Lupinus micranthus*, *Lupinus hispanicus*, *Lupinus varius*, or *Lupinus anatolicus*.

Hypocholesterolemic Effects

The hypocholesterolemic effects of *Lupinus* species—particularly *Lupinus albus* and *Lupinus angustifolius* —have been widely investigated for their ability to regulate lipid metabolism and manage hypercholesterolemia. These beneficial effects are primarily attributed to the protein composition, bioactive peptides, dietary fiber, and phytochemical content found in lupin seeds.

Lupin-derived peptides also promote cholesterol catabolism and excretion by increasing bile acid production, facilitating the elimination of cholesterol from the body. The high soluble fiber content in lupin seeds contributes further to this effect by binding bile acids in the intestine, thereby interrupting enterohepatic recirculation and enhancing cholesterol clearance (Hodgson et al., 2010; Tesarowicz et al., 2022). In animal studies, lupin protein sources have been demonstrated to have cholesterol-lowering potential. For instance, in a study comparing *L. angustifolius* with casein in pigs fed a high-cholesterol diet, lupin significantly reduced plasma cholesterol levels (Martins et al., 2005). Similarly, Fontanari et al. (2012) reported that both whole lupin seeds and protein isolates significantly lowered serum cholesterol in animal models. This effect was associated with the inhibition of 3-hydroxy-3-methylglutaryl-coenzyme A reductase (HMG-CoA reductase)—the rate-limiting enzyme in cholesterol biosynthesis—regulated via sterol regulatory element-binding proteins (SREBPs) (Fontanari et al., 2012). Both human and animal studies support the efficacy of yellow lupin (*L. luteus*), *L. albus*, and *L. angustifolius* in improving lipid profiles. These effects are believed to result from the unique amino acid composition and structure of lupin proteins. The protein hydrolysates from these species also exhibit antioxidant properties, which help combat oxidative stress, a key factor in the development of hyperlipidemia and cardiovascular disease (Tesarowicz et al., 2022).

Flavonoids, saponins, and other phenolic compounds in lupin seeds further contribute to lipid-lowering effects. These compounds enhance endothelial function and reduce intestinal cholesterol absorption by altering micellar solubility and inhibiting cholesterol transport mechanisms (Zhong et al., 2012). Additionally, regular lupin consumption has been linked to increased satiety, which can support weight management and indirectly impact serum lipid levels (Yildirim et al., 2020).

Dietary interventions involving lupin-based foods have consistently demonstrated improvements in lipid profiles. For example, Hodgson et al. (2010) reported that increasing lupin-derived protein and fiber intake led to reductions in total cholesterol and triglyceride levels in overweight individuals. These outcomes were attributed to the synergistic effects of energy-dense nutrients and bioactive compounds in lupin that act on lipid metabolism pathways (Hodgson et al., 2010).

In conclusion, *Lupinus* species exhibit robust hypocholesterolemic activity through multiple mechanisms, including inhibition of cholesterol synthesis (via HMG-CoA reductase), the promotion of bile acid-mediated excretion, the inhibition of intestinal lipid absorption, and the improvement of antioxidant defenses. These properties reinforce the value of lupin as a functional food for cardiovascular health and metabolic regulation.

There are no reported studies investigating the antihypertensive properties of *Lupinus micranthus*, *Lupinus hispanicus*, *Lupinus varius*, or *Lupinus anatolicus*.

Anticholinergic Effects

In addition to their well-documented antioxidant properties, certain *Lupinus* species particularly *Lupinus luteus* contain bioactive quinolizidine alkaloids, such as lupanine and sparteine, that exhibit mild anticholinergic activity. These alkaloids have drawn scientific interest due to their potential pharmacological applications in neurological disorders, especially those involving cholinergic dysregulation, such as Alzheimer's disease.

Research suggests that lupanine and related compounds act as reversible inhibitors of acetylcholinesterase (AChE), the enzyme responsible for the breakdown of acetylcholine in the synaptic cleft. By inhibiting AChE, these alkaloids can increase the availability of acetylcholine at synaptic junctions, thereby enhancing cholinergic neurotransmission. This mechanism underpins the rationale for their potential use as adjunct therapies in neurodegenerative conditions characterized by acetylcholine deficiency (Hassine et al., 2021).

Although their anticholinergic effects are generally considered mild compared to synthetic cholinesterase inhibitors, the natural origin and additional bioactivities of these alkaloids—such as antioxidant and antimicrobial effects suggest they may contribute to multifunctional therapeutic strategies. However, the therapeutic window is narrow, as these same alkaloids are also associated with toxicity risks at higher concentrations, including neurotoxicity and cardiotoxicity (Ozkaya et al., 2021).

In summary, alkaloids such as lupanine and sparteine present in *L. luteus* exhibit mild anticholinergic effects through AChE inhibition, supporting their potential role in managing neurodegenerative diseases. Further studies are needed to determine their safety profile, optimal dosing, and efficacy in clinical settings.

There are no reported studies investigating the anticholinergic properties of *Lupinus micranthus*, *L. hispanicus*, *L. varius*, *L. angustifolius*, or *L. anatolicus*

Anticancer Effects

The anticancer potential of *Lupinus* species—especially *Lupinus albus* and *L. angustifolius*—has attracted growing scientific attention due to their diverse phytochemical content, including flavonoids, alkaloids, peptides, and dietary fiber. These compounds are known to exert anticancer effects via multiple cellular and molecular mechanisms.

A particularly noteworthy compound is genistein, an isoflavone in lupin, which has been shown to inhibit the proliferation of various cancer cell lines, including ovarian carcinoma (SK-OV-3) cells. Genistein induces apoptosis through cell cycle arrest and the activation of pro-apoptotic factors such as caspases, as well as modulation of the MAPK/ERK signaling pathways that regulate cell proliferation and survival (Antosiak et al., 2017).

Additionally, the octapeptide GPETAFLR, derived from hydrolyzed *L. angustifolius* protein, has been found to exert immunomodulatory effects that contribute to anticancer activity. This peptide enhances anti-inflammatory responses and promotes immune surveillance by skewing monocyte differentiation toward the M2 macrophage phenotype, which is associated with tissue repair and immune regulation (Montserrat-de la Paz et al., 2019). The antioxidant properties of lupin phytochemicals, particularly polyphenols and flavonoids, are believed to prevent carcinogenesis by reducing oxidative stress and preventing DNA damage. Danciu et al. (2017) demonstrated that high total phenolic content in lupin seeds correlates with the inhibition of tumor cell growth by oxidative stress suppression(Danciu et al., 2017).

Lupin proteins have also been linked to improved lipid metabolism, which may reduce the risk of cancer. Given the established association between hyperlipidemia and various malignancies, the cholesterol-lowering properties of lupin seeds (Fontanari et al., 2012) may have indirect anticancer benefits.

Furthermore, the dietary fiber content of lupin contributes to its anticancer potential, especially in the context of colorectal cancer. Dietary fiber binds bile acids and promotes their excretion, reducing their potential carcinogenic effects in the colon (Danciu et al., 2017). In addition, fiber supports gut microbiota health, which has been linked to immune system modulation and tumor suppression.

In conclusion, *Lupinus* species exhibit multifaceted anticancer effects mediated through antioxidant activity, immune modulation, apoptosis induction, and dietary fiber functions. These findings underscore the potential of lupin-derived compounds as natural adjuncts in cancer prevention and management strategies. Further research is warranted to clarify their mechanisms and explore clinical applications.

There are no reported studies investigating the anticholinergic properties of *L. micranthus*, *L. hispanicus*, *L. varius*, or *L. anatolicus*.

Antimicrobial, Antifungal, and Antiparasitic Effects

Lupinus species have demonstrated broad-spectrum antimicrobial properties, making them a subject of increasing interest in the search for natural antimicrobial agents. These effects are primarily attributed to the presence of various bioactive compounds, including alkaloids, polyphenols, flavonoids, peptides, and saponins found in lupin seeds.

Ethanolic extracts of *Lupinus albus* and *Lupinus angustifolius* have been shown to possess potent antibacterial properties against both Gram-positive and Gram-negative bacteria, including *Escherichia coli* and *Bacillus subtilis* (Rani & Rani, 2025). The antimicrobial action of phenolic compounds is largely related to their ability to disrupt bacterial cell membranes, inhibit essential metabolic enzymes, and interfere with nucleic acid synthesis.

The efficacy of both germinated and ungerminated seed extracts of lupin has also been validated *in vitro* models. These extracts exhibited significant reductions in microbial loads, suggesting a potential role in controlling foodborne pathogens and promoting food safety (Andor et al., 2016). Specific isoflavones and cinnamic acid derivatives in lupin extracts are believed to enhance this antimicrobial action(Andor et al., 2016).

Additionally, alkaloid-rich extracts from lupin have demonstrated strong antibacterial activity against antibiotic-resistant clinical isolates such as *Klebsiella pneumoniae* and *Pseudomonas aeruginosa*—pathogens commonly associated with hospital-acquired infections (Romeo et al., 2018).

Fermentation of lupin proteins further enhances their antimicrobial activity. For example, fermentation with Lactobacillus species reduced the molecular weight of *L. angustifolius* proteins, thereby increasing their bioactivity against microbial pathogens (Bartkiene et al., 2019). Saponins another class of lupin phytochemicals—exhibit antimicrobial action by disrupting microbial membrane integrity and leading to cell lysis (Ishaq et al., 2022).

The anthelmintic properties of lupin alkaloids have also been documented. *In vitro* studies verified that alkaloid extracts from *L. albus* inhibit the migration of larvae from parasitic nematodes such as *Haemonchus contortus* and *Teladorsagia circumcincta*, both of which are major gastrointestinal parasites in ruminants. This effect was attributed to the interaction of alkaloids with the nematodes' acetylcholine receptors, disrupting neuromuscular function (Dubois et al., 2019).

Regarding antifungal effects, extracts of *Lupinus albescens* demonstrated high antifungal activity against *Fusarium oxysporum* and *F. verticillioides*, pathogens responsible for significant crop losses. Supercritical CO_2 and liquefied petroleum gas extraction methods yielded extracts that inhibited fungal growth by over 60%, suggesting potential for use as eco-friendly fungicides (Confortin et al., 2019). Further analysis of quinolizidine alkaloids in *Lupinus* species revealed that their antifungal efficacy varies based on chemical structure. Targeted extraction and chemical characterization could pave the way for the development of novel antifungal agents (Cely-Veloza et al., 2022, 2023). Lupin alkaloids have also shown efficacy against *Candida albicans* and other opportunistic fungi, with studies highlighting their broad-spectrum antifungal potential (Erdemoglu et al., 2007).

In addition, silver nanoparticles (AgNPs) synthesized using *Lupinus albus* extracts have demonstrated acaricidal, larvicidal, and repellent activity against the camel tick (*Hyalomma dromedarii*). These nanoparticles caused 100% mortality at specific concentrations, significantly reduced egg-laying parameters, suppressed acetylcholinesterase (AChE) activity, and elevated oxidative stress levels in target organisms (Majeed et al., 2023).

Furthermore, allelopathic interactions between lupins and neighboring plant species suggest that their root exudates may have antifungal properties, contributing to soil health and plant disease resistance (Georgieva et al., 2015; Prass et al., 2022; Wurst et al., 2010).

In conclusion, the antimicrobial, antifungal, and antiparasitic effects of *Lupinus* species are multifactorial and involve a rich array of phytochemicals. These findings support the potential use of lupin-based extracts as natural antimicrobial agents in food preservation, animal health, crop protection, and even human therapeutics.

Immunomodulatory Effects

The immunomodulatory potential of *Lupinus* species has gained increasing scientific interest, particularly regarding their ability to modulate cytokine production, support immune cell function, and mitigate inflammatory responses. These effects are primarily attributed to the presence of flavonoids, alkaloids, peptides, and other secondary metabolites found in lupin seeds.

Flavonoids—abundant polyphenolic compounds in *Lupinus*—are well known for their antioxidant and anti-inflammatory properties, but they also play a critical role in immune modulation. These compounds can regulate the release of pro-inflammatory cytokines such as interleukin-1 (IL-1) and interleukin-2 (IL-2), which are crucial for T-cell activation and proliferation (Hoensch & Weigmann, 2018; Kamboh, 2015). By inhibiting overactivation of immune effectors, flavonoids help maintain immune balance and reduce the risk of autoimmune reactions. Mierziak et al. (2014) further highlighted the role of plant flavonoids in environmental stress and immune signaling (Mierziak et al., 2014).

Alkaloids, particularly lupanine, also contribute to immunomodulatory effects by exerting metabolic and antimicrobial actions. Lupanine has been shown to regulate glucose metabolism by modulating KATP channels and insulin gene expression, while also enhancing host defense mechanisms (Wiedemann et al., 2015). This highlights the complex interplay between metabolic regulation and immune function, where phytochemicals simultaneously improve systemic and immune health.

Tannins found in lupin seeds have also been related to the stimulation of macrophage activity and enhanced cytokine secretion. These effects are consistent with studies demonstrating that plant-derived secondary metabolites exhibit antiviral properties and support immune responses against a broad spectrum of pathogens (Jumaa et al., 2021).

The GPETAFLR peptide, derived from *L. angustifolius* protein hydrolysate, has demonstrated dual anti-inflammatory and immunoregulatory effects. In monocyte-derived osteoclasts, this peptide downregulated pro-inflammatory cytokines such as TNF-α, IL-1β, and IL-6, while simultaneously upregulating anti-inflammatory cytokines IL-4 and IL-10. Additionally, in microglial cells and high-fat diet-induced obese mice, GPETAFLR was shown to promote M2 macrophage polarization and reduce neuroinflammation, thus supporting central nervous system (CNS) homeostasis (Millán-Linares et al., 2014; Montserrat-de la Paz et al., 2019).

Other studies have focused on specific lupin varieties such as *L. albus*, whose protein and lipid compositions contribute to improved immune status. Dietary consumption of these legumes has been associated with decreased levels of inflammatory markers, reinforcing their potential as functional foods aimed at immune enhancement (Carvajal-Larenas et al., 2016; Khan et al., 2015; Pastor-Cavada et al., 2010; Yildirim et al., 2020).

The globulin γ-conglutin, one of the major proteins in lupin seeds, has also been associated with improved metabolic and immune outcomes. It plays a role in energy metabolism in muscle tissue and may activate immune-related signaling cascades (Rosa Lovati et al., 2012).

Animal studies have further demonstrated that *Lupinus* extracts can modulate immune responses, increasing levels of pro-inflammatory cytokines (interferon-gamma (IFN-γ)), while decreasing levels of immunosuppressive cytokines (IL-10). This immunostimulatory balance may enhance host resistance to infections and inflammation (Gaur et al., 2008).

A noteworthy application of lupin in animal health includes its use in aquaculture. For example, Weiß et al. (2020) demonstrated that incorporation of lupin seed meal into the diet of white-legged shrimp (*Litopenaeus vannamei*) improved immune function, indicating that the immunomodulatory benefits of Lupinus species extend across species(Weiss et al., 2020).

In conclusion, *Lupinus* species exhibit pronounced immunomodulatory activity through multiple phytochemicals that influence cytokine profiles, macrophage polarization, and immune system regulation. These findings support the development of lupin-based dietary strategies to enhance immunity and prevent immune-related disorders in humans and animals.

Side Effects

Despite the numerous health benefits associated with Lupinus species, potential adverse effects must be considered, particularly those related to their alkaloid and allergenic content. The most significant concern is the risk of toxicity due to quinolizidine alkaloids—naturally occurring compounds found especially in L. luteus, L. angustifolius, and L. albus. These alkaloids may lead to neurotoxic effects, allergic reactions, and gastrointestinal disturbances if consumed in excessive amounts or without proper processing.

Some lupin varieties contain alkaloid levels that exceed the recommended safety threshold of 200 mg/kg, as established by food safety authorities (Boukid & Pasqualone, 2022). Unprocessed or poorly processed seeds of such varieties have been linked to acute poisoning symptoms, including nausea, vomiting, tremors, convulsions, and impaired motor coordination (Boschin et al., 2008; Frick et al., 2017). In particular, lupanine and sparteine have been identified as the primary neurotoxic agents.

L. angustifolius, while considered a "sweet" lupin species, can still contain significant amounts of lupanine, which has been associated with anticholinergic symptoms when consumed raw or inadequately prepared (Daverio et al., 2014; Ozkaya et al., 2021). Lupin proteins, particularly α- and β-conglutins, are also known allergens. Sensitization to lupin has been reported, *in particular* among individuals allergic to peanuts or soybeans, due to cross-reactivity. Clinical cases have documented mild symptoms (e.g., bloating, rash) as well as severe reactions such as anaphylaxis after lupin ingestion in peanut-sensitive individuals (Peeters et al., 2009; Sanz et al., 2010; Villa et al., 2020).

Additionally, the high fiber content of *L. albus*, *L. angustifolius*, and *L. luteus*—particularly α-galactosides—can cause gastrointestinal side effects such as bloating, flatulence, abdominal pain, and diarrhea in individuals with sensitive digestive systems (Zraly et al., 2007). These effects are responsible for the fermentation of fibers in the colon, resulting in gas production.

Severe cases of poisoning have been documented in both children and adults following the ingestion of lupin products containing high levels of alkaloids, reinforcing the importance of appropriate processing methods such as soaking, cooking, and fermentation to reduce alkaloid concentrations to safe levels (Bloothooft et al., 2025; Yeheyis et al., 2011). Although thermal processing may reduce allergenicity to some extent, it does not eliminate it (Villa et al., 2024). Even though "sweet" lupin cultivars have been developed to contain low levels of alkaloids, the unintentional consumption of wild or improperly labeled high-alkaloid varieties still poses a risk (Gresta et al., 2017).

In summary, while *Lupinus* species offer considerable health benefits, attention must be given to their potential side effects, particularly alkaloid toxicity and allergenicity. Ensuring the consumption of properly processed low-alkaloid cultivars is essential for safe use in both human and animal nutrition. Continued monitoring and consumer education remain important for minimizing health risks.

Specific studies on the adverse effects of *Lupinus micranthus* are limited.

Teratogenicity

Although *Lupinus* species are generally considered safe when properly processed and consumed in moderation, certain alkaloid-rich varieties have been associated with teratogenic effects, particularly in livestock. Chronic exposure to quinolizidine alkaloids—specifically anagyrine and ammodendrine—has been shown to cause developmental abnormalities during gestation (S. T. Lee et al., 2008).

These effects have been primarily reported in the context of North American lupin species such as *Lupinus leucophyllus* and *L. sulphureus*. In livestock, exposure to these alkaloids during early pregnancy has been linked to a condition known as "crooked calf disease," which involves skeletal deformities and joint malformations (S. T. Lee et al., 2008; Stephen T. Lee et al., 2007, 2019). The teratogenic outcomes are influenced by the alkaloid concentration, duration of exposure, and physiological status (e.g., body condition) of the pregnant animals(Boschin & Resta, 2013; Green et al., 2013).

Studies have explored non-invasive biomarkers (e.g., analysis of hair, earwax, nasal mucus, and oral fluid) to monitor livestock exposure to teratogenic lupin species, highlighting practical approaches for early detection and prevention in animal husbandry (Stephen T. Lee et al., 2019). Importantly, such teratogenic effects have not been documented for lupin species commonly cultivated in Turkey, including *L. albus*, *L. angustifolius*, *L. luteus*, or *L. anatolicus*. However, due to the structural similarities among quinolizidine alkaloids across species, the potential for reproductive toxicity cannot be entirely excluded without species-specific toxicological evaluation.

In conclusion, teratogenic effects have been primarily associated with specific alkaloids in wild lupin species, especially in livestock exposed during critical periods of gestation. Although no such effects have been reported for *Lupinus* species cultivated in Turkey, continued vigilance, proper species identification, and alkaloid profiling are essential to ensure safety in both human and veterinary contexts.

Discussion

Lupinus species, particularly ***Lupinus albus*** (white lupin), have emerged as prominent subjects in both nutritional and pharmacological research due to their broad spectrum of biological activities. As members of the Fabaceae family, lupins are recognized for their high protein content, abundant dietary fiber, and low-fat levels, making them an attractive alternative food source for both human and animal consumption (Pereira et al., 2022).

The richness of lupin seeds in bioactive compounds—such as alkaloids, flavonoids, peptides, and polyphenols—has positioned them as potential nutraceuticals: natural products that exert beneficial effects in the prevention and management of chronic diseases. A growing body of evidence from animal studies supports their pharmacological effects, including antioxidant, antidiabetic, anti-inflammatory, and lipid-lowering properties (Andor et al., 2016).

In the context of animal health and nutrition, lupin seeds offer multiple advantages. Their high protein and fiber content **contribute** to improved digestion, enhanced immune status, and better nutrient utilization. These attributes make lupin-derived feed an effective and sustainable alternative to traditional protein sources in livestock production systems. Research has shown that the inclusion of lupin meal in animal diets improves feed conversion ratios, promotes weight gain, and supports overall animal health (Pereira et al., 2022).

The method of processing lupin seeds significantly influences their bioactive potential. For instance, fermentation with probiotic bacteria such as ***Lactobacillus*** species has been shown to enhance the nutritional profile of lupin flour and improve its palatability and digestibility in **animal nutrition.** Additionally, **these** processing methods can increase the bioavailability of peptides and other functional compounds, expanding the potential of lupin as an ingredient in nutritionally enriched food and feed products (Bartkiene et al., 2019; Pereira et al., 2022).

Furthermore, the versatility of *L. albus* and *L. angustifolius* as both food and functional agents is reflected in their promising pharmacological profiles. These species provide not only nutritional support but also therapeutic effects in the context of metabolic disorders, immune dysfunction, and oxidative stress. Their applications range from clinical nutrition to veterinary medicine, making them valuable in both human health and animal husbandry.

In conclusion, *Lupinus* species—particularly *L. albus* and ***L. angustifolius***—exhibit a wide range of beneficial properties that align with the growing demand for sustainable, plant-based nutraceuticals. Their role in promoting health, managing chronic conditions, and enhancing animal welfare highlights their dual utility as both food and medicine. Pharmacological and biological activity studies conducted on Lupinus species naturally occurring in Turkey are quite limited in number and scope in the existing literature. This limitation prevents the full elucidation of the biological activity profiles, mechanisms of action, and potential therapeutic applications of these species. However, it is notable that ***Lupinus*** species are distinguished by their abundant phytochemical content, encompassing alkaloids, phenolic compounds, proteins, and bioactive peptides. These characteristics suggest a potential for action against various diseases, including anticancer, antioxidant, anti-inflammatory, antimicrobial, and metabolic disorders. Consequently, there is an imperative for multi-centre, interdisciplinary research that characterises the phytochemical composition of different ***Lupinus*** species cultivated in Turkey in detail, conducts comprehensive biological activity analyses in cell culture and animal models, and transfers the obtained data to clinical studies. Such studies are of great importance for revealing the pharmaceutical potential of local plant genetic resources and for developing new opportunities for biotechnological and industrial applications. Further investigations are needed to fully integrate lupin-based strategies into veterinary and clinical practice, particularly in the context of developing functional food and sustainable livestock production.

Additionally, scientific studies should be complete, including drug-plant or plant-plant interactions, mutagenicity, contraindications, route of administration, dosage, use in pregnancy and lactation, pediatric use, and preparations or herbal products containing *Lupinus* species in Turkey.

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Embedding Aluminum in Cementitious Systems: Risks, Mitigation, And Future Perspectives

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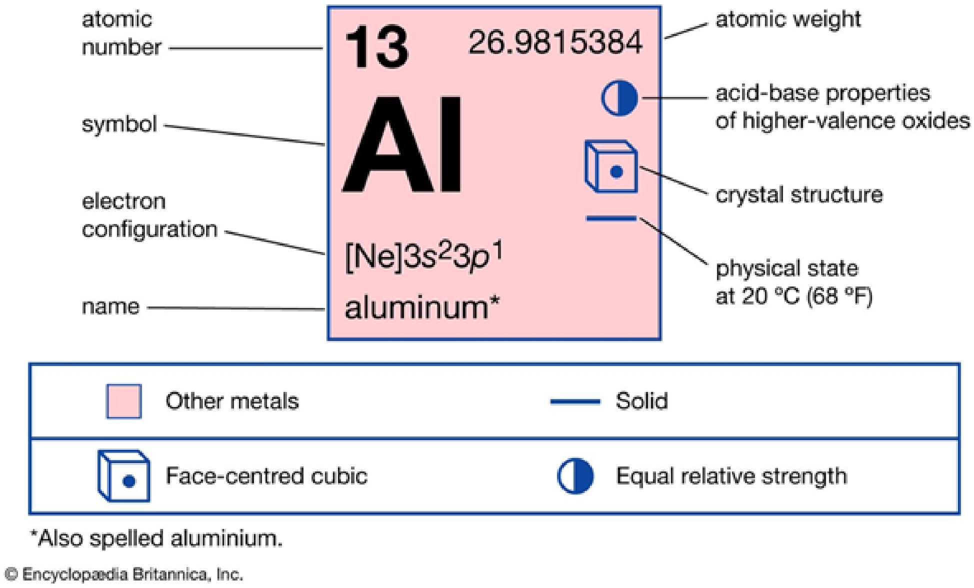
Introduction

Aluminum, a non-ferrous metal characterized by low density and strong corrosion resistance, is extensively utilized across many industrial sectors (Polmear et al., 2017). In building materials, it offers key advantages such as light weight and formability (**Figure 1**), making it suitable for elements like window frames, panels, and exterior façades. Nevertheless, the metal's strong chemical reactivity in alkaline media poses significant challenges for maintaining long-term stability within cement-based composites. Upon exposure to air, aluminum instantly develops a compact and protective oxide layer that stabilizes the surface in neutral or slightly acidic media. In the highly alkaline pore solution typical of ordinary Portland cement (OPC), however, this film gradually deteriorates. As a consequence, electrochemical activity accelerates the dissolution of aluminum, accompanied by hydrogen generation and the accumulation of expansive hydroxide or oxide phases. Such processes not only degrade the metal but also damage the integrity of the adjacent cementitious matrix through cracking, blistering, and detachment.

Therefore, a critical engineering question arises: *Can aluminum be safely embedded in concrete, and if so, under what controlled conditions?*

Figure 1

Properties of the Element Aluminum



Explanatory note. The figure presents the fundamental physical and mechanical properties of aluminum relevant to its application in cementitious systems.

There remains considerable debate regarding the interaction of aluminum, whose role in transportation, aviation, and architectural applications is well established, with cementitious system materials. In OPC systems, the highly alkaline pore solution (pH ≈ 12–13.5) destabilizes the protective oxide film, leading to rapid dissolution, hydrogen evolution, and the accumulation of expansive corrosion products. These phenomena collectively threaten both the durability of aluminum components and the structural integrity of concrete.

International standards such as Eurocode 9 (CEN, 2009), ACI (2018), and the Concrete Institute (2025) restrict the direct embedding of untreated aluminum in concrete. Nonetheless, recent studies have focused on mitigation strategies and novel applications (Abdalla et. al., 2020; Runningen et. al., 2021; Elsamak et. al., 2025). These include the incorporation of supplementary cementitious materials (SCMs) to lower pore solution alkalinity, the use of alternative binders such as magnesium potassium phosphate cement (MKPC) with reduced pH, and the application of advanced protective coatings to prevent direct contact between aluminum and the cement matrix. Moreover, aluminum has been investigated as a structural component in concrete-filled aluminum tube (CFAT/ATCC) systems and as a recycled additive to enhance mechanical, thermal, and multifunctional properties of cementitious composites. These emerging approaches align with sustainable construction principles by reducing carbon emissions and promoting circular material use.

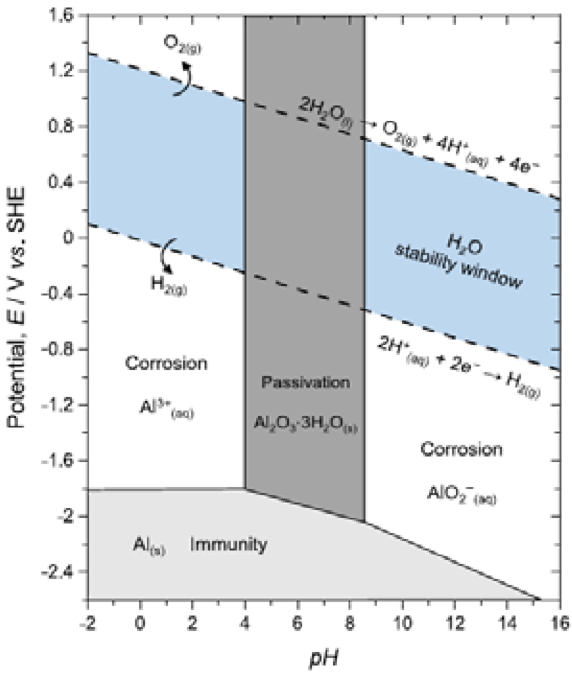
The objective of this chapter is to systematically evaluate the electrochemical behavior of aluminum in cementitious environments, to summarize the requirements of international standards, and to highlight advances in mitigation and emerging applications. Particular emphasis is placed on corrosion mechanisms, galvanic interactions with steel reinforcement, and the potential contribution of aluminum waste to sustainable construction. By identifying research gaps and future perspectives, this chapter aims to provide a comprehensive framework for assessing the safe and effective integration of aluminum into modern concrete technologies.

Electrochemical Behaviour of Aluminum

The electrochemical response of aluminum varies considerably depending on the composition of the surrounding electrolyte. Under highly alkaline conditions, hydroxide ions disrupt the protective oxide barrier, reflecting the strong interaction between aluminum and water molecules. Consequently, the metal acquires a markedly negative potential and experiences rapid dissolution, accompanied by hydrogen generation and the production of aluminate species. In aluminum alloys reinforced with ceramic particles, the electrochemical behavior may also differ due to altered surface characteristics and microstructural uniformity (Uygur et al., 2004; Uygur, 2024). Under these conditions, aluminum can also undergo anodic dissolution at high current densities without significant polarization (Hernández et. al., 2011), as illustrated in the Pourbaix diagram summarizing aluminum in aqueous environments (**Figure 2**).

Figure 2

Pourbaix Diagram of Aluminum in Aqueous Solution (Leung et. al. 2021)



Explanatory note. The diagram illustrates the electrochemical stability of aluminum species as a function of pH and potential, highlighting the instability of aluminum in highly alkaline media.

When aluminum comes into contact with steel reinforcement in concrete, a galvanic cell is established due to the potential difference between the two metals. Aluminum acts as the anode and undergoes dissolution, while steel behaves as the cathode, accelerating localized corrosion. As a result, hydrogen gas evolution and severe pitting corrosion occur at the interface of aluminum and steel in the presence of chloride ions. Studies on discontinuously reinforced aluminum matrix composites demonstrated that fatigue life and crack propagation are strongly influenced by particle size and distribution.

Concrete and GFRC (Glass Fiber Reinforced Concrete), as cementitious system materials, typically create highly alkaline environments with a pH range of 11–13. According to the Pourbaix diagram, at these high pH levels and depending on the electrochemical potential, aluminum tends to corrode by dissolving into AlO_2^- ions. Notably, at pH values above 9, the protective passive layer on aluminum deteriorates, losing its effectiveness. Therefore, direct contact between aluminum and such alkaline environments poses a risk to the material's structural integrity.

$$2Al + 6H_2O + 2OH^- \rightarrow 2[Al(OH)_4]^- + 3H_2\uparrow \quad (1)$$

Bare (uncoated) aluminum should not be embedded directly in fresh concrete. The highly alkaline pore solution (pH ~12–13.5) attacks aluminum, forming aluminum hydroxide and releasing hydrogen gas. This reaction can produce voids, loss of bond, surface blistering, and long-term corrosion of the aluminum element. Supplementary cementitious materials (SCMs) such as fly ash and silica fume have been shown to reduce pore solution alkalinity, thereby slowing down aluminum corrosion. Runningen et al. (2021) reported that aluminum alloys embedded in cement pastes with a high SCM content exhibited greater chemical stability and reduced hydrogen gas evolution than plain OPC systems.

International standards are quite clear regarding the usability of aluminum in concrete, and they stipulate that aluminum can be used in concrete for various applications, including construction, infrastructure, and engineering projects. The American Concrete Institute (ACI; 2018) has stated in its documentation that direct contact between untreated aluminum and fresh concrete results in the release of copious amounts of hydrogen gas and the formation of surface defects. Consequently, the embedding of aluminum without a protective coating is strictly prohibited. Similarly, Eurocode 9 (CEN 1999-1-1:2009, Annex D.3.4) stipulates that aluminum must be coated with at least two layers of heavy-duty bituminous paint or hot bitumen when embedded in concrete and that the coating must extend at least 75 mm above the concrete surface. It also requires the use of plasticised coal tar in chlorinated concrete and strictly prohibits direct electrical contact between steel and aluminum. The Concrete Society's current guide also reports that aluminum undergoes severe initial attack in environments containing calcium hydroxide; that the risk of cracking and spalling increases due to hydrogen gas formation; that this effect is exacerbated when calcium chloride additives are used; and that prestressed concrete systems carry a risk of hydrogen embrittlement. These standards show that there is a general agreement: aluminum cannot be safely put into concrete without strong ways to protect it. The focus on coatings, electrical insulation, and design-specific measures is a result of the understanding that aluminum's natural instability in alkaline pore solutions can lead to risks that affect the whole structure.

A comparative assessment of international standards reveals converging principles. Although developed within different regulatory contexts, ACI, Eurocode 9, and the Concrete Society guidelines align on several critical points, particularly regarding coating requirements, chloride restrictions, and the necessity of isolating aluminum from steel.

- **ACI (2018):** It is stated that untreated aluminum should not come into direct contact with fresh concrete; otherwise, intense hydrogen gas release and surface defects will occur. Therefore, embedding operations must be carried out using appropriate protective coatings.
- **Eurocode 9 (CEN, 2009):** When aluminum is embedded in concrete, it must be coated with at least two layers of bituminous paint or hot bitumen. The coating must extend at least 75 mm above the concrete surface. Additionally, direct electrical contact with steel is strictly prohibited, and the use of plasticised coal tar is recommended for chlorinated concrete.
- **Concrete Society (2025):** It emphasises that aluminum undergoes severe corrosion in environments containing calcium hydroxide and, in particular, calcium chloride; that the risk of cracking and spalling increases due to hydrogen release; and that special attention must be paid to the risk of hydrogen embrittlement in prestressed concrete.

A study by Herting and Odnevall (2021) investigated the long-term corrosion behavior of aluminum (Al) and zinc (Zn) embedded in concrete under anaerobic conditions, simulating the Swedish repository environment for low- and intermediate-level radioactive waste. The samples were immersed in artificial groundwater (AGW) for up to two years. Aluminum exhibited high initial corrosion rates, which gradually decreased and stabilized over time. After 104 weeks, some Al-containing concrete cylinders developed cracks, attributed to hydrogen gas evolution and expansion of corrosion products. Zinc samples, in contrast, showed lower corrosion rates and maintained the structural integrity of the concrete. The study concluded that AGW exposure tests can reliably predict long-term corrosion performance of metals embedded in concrete under similar conditions.

Figure 3

Representative concrete cylinder after two years, excluding two aluminum-containing samples.

Figure 3. (a) Concrete cylinder representative for all samples and time periods except two Al containing cylinders (out of five) exposed for two years and (b) Concrete cylinder containing Al that cracked after two years of exposure.

Explanatory note. Cracking observed in aluminum-containing samples results from internal hydrogen gas evolution and volumetric expansion of corrosion products.

After two years of exposure, 40% of the Al-containing concrete cylinders developed visible structural cracks (up to 3 mm wide), compromising the integrity of the concrete matrix. These cracks originated from internal stresses due to the corrosion process, as shown in **Figure 3b**, while no such degradation was observed in zinc-containing samples (**Figure 3a**). This confirms that aluminum poses a greater risk to concrete durability under repository conditions, whereas zinc exhibits more stable long-term behaviour.

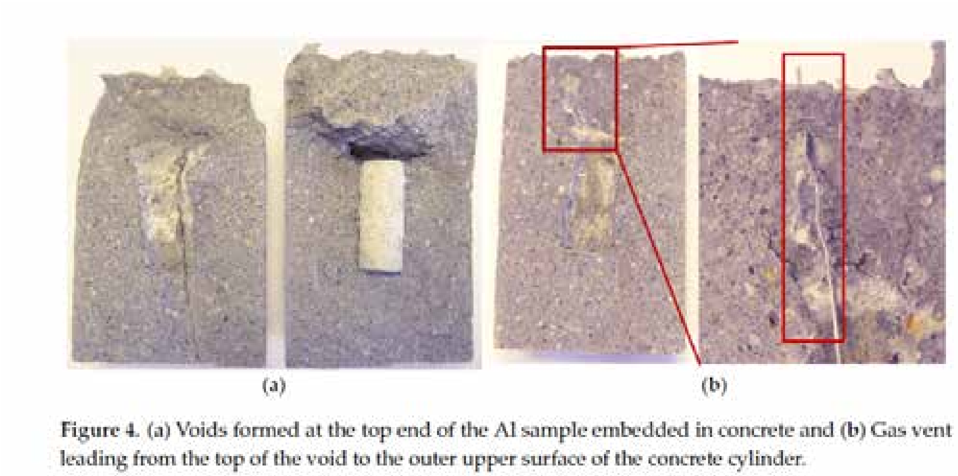
Alternative Binding Systems and Corrosion Behavior

Traditional Portland cement (OPC) has high alkalinity (pH 12.5–13.5), and in this environment, aluminum rapidly reacts with hydroxide ions to produce hydrogen gas. The formation of large-volume hydrated oxide products (e.g., bayerite, gibbsite) on the aluminum surface and the initiation of cracks in the concrete matrix are caused by this process (Korec et. al., 2023; Abi Aad et. al., 2017). In recent years, studies have been conducted on alternative binding systems to address this problem. Notably, magnesium potassium phosphate cement (MKPC) engenders a distinctly more propitious chemical milieu for aluminum by virtue of its lower pH values (4–9). Perona et al. (2023) investigated A1050 and AA5754 aluminum alloys in both OPC and MKPC systems. They reported that, after 15 days, 11.6–17.8 L/m² of hydrogen gas was released in the OPC system. In the MKPC system, however, this value was only 0.14–0.33 L/m². These results suggest that MKPC can reduce aluminum corrosion by at least one order of magnitude. Additionally, evaluations by Fernández-García and Alonso (2025) indicate that while low corrosion current and H2 volume were observed in the MKPC environment during the initial stages, long-term alkalization may weaken this protective effect. These findings suggest that MKPC could be a more suitable alternative to conventional binders for aluminum, particularly for immobilising nuclear waste and for use in concrete applications requiring special durability.

As shown in **Figure 4a**, corrosion of aluminum in the high-pH concrete environment led to the formation of visible voids above the embedded metal, caused by rapid hydrogen gas evolution during the early stages of exposure. This gas generation weakened the adhesion between the aluminum and the surrounding concrete. **Figure 4b** illustrates a gas vent channel extending from the void to the outer surface of the concrete cylinder, providing a pathway for gas escape. These features indicate that the corrosion of aluminum not only affects the metal but also alters the structural continuity of the concrete matrix.

Figure 4

Voids formed at the top end of the aluminum sample embedded in concrete, and the gas vent extending from these voids to the outer surface of the concrete cylinder is shown.



Explanatory note. Gas vent channels originating from hydrogen evolution are visible, illustrating the effect of aluminum corrosion on the surrounding concrete matrix.

Calderón et al. (2022) investigated the corrosion behavior of aluminum embedded in cementitious environments with high alkalinity (pH > 12). The study involved immersing aluminum samples in a synthetic pore solution and analyzing the resulting corrosion products using SEM, EDX, and XRD. The findings revealed the formation of hydrated aluminum oxide phases, which expand and generate internal stresses in the cement matrix. These stresses are capable of initiating cracks, potentially compromising the structural integrity of the system. The results contribute valuable insights into the long-term electrochemical stability of aluminum in concrete and similar materials.

Figure 5 presents a scanning electron microscopy (SEM) image of an aluminum sample surface after two weeks of exposure to a high-pH synthetic pore solution (pH ≈ 13.5). The image reveals the formation of dense and irregular corrosion products covering the surface. These products are primarily hydrated aluminum oxides, such as bayerite and gibbsite. The morphology indicates significant volume expansion, leading to surface roughness and localized delamination. This supports the conclusion that aluminum corrosion in alkaline environments can generate internal stresses, contributing to cracking and potential degradation of the surrounding cementitious matrix.

Figure 5

EM images of Al plates embedded in Portland cement pastes hydrated for three days.

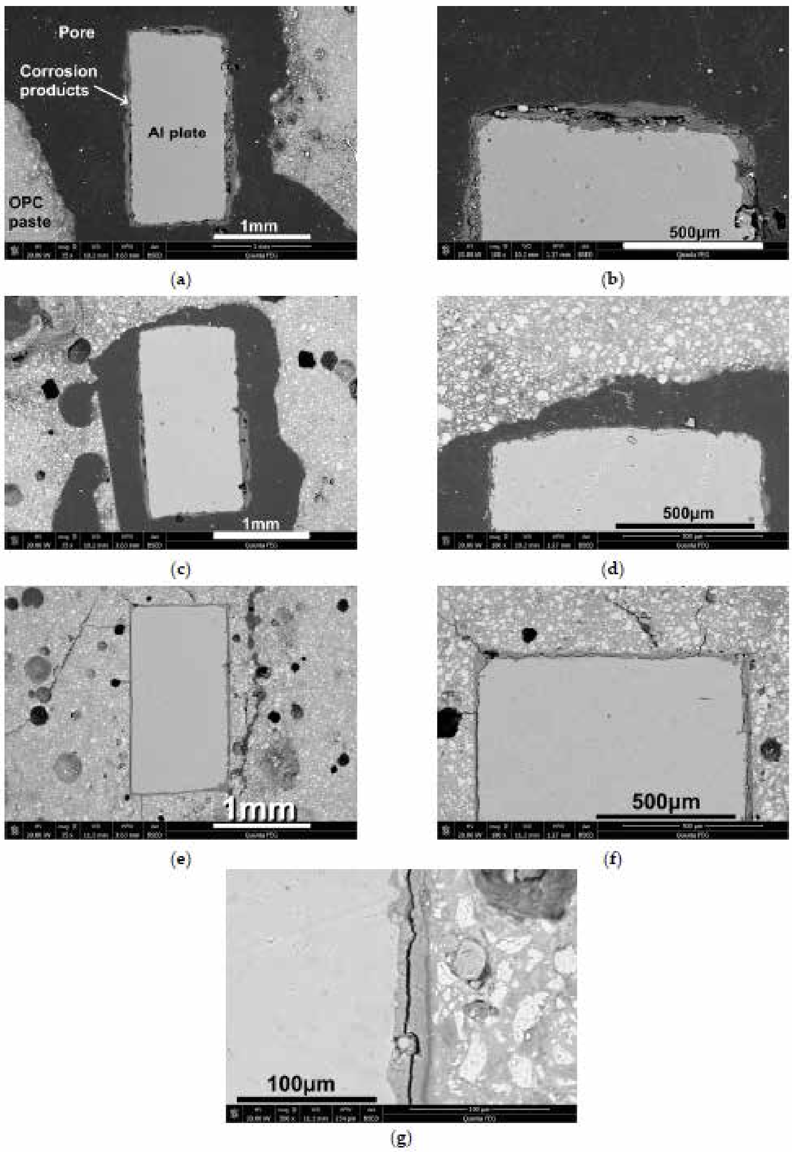


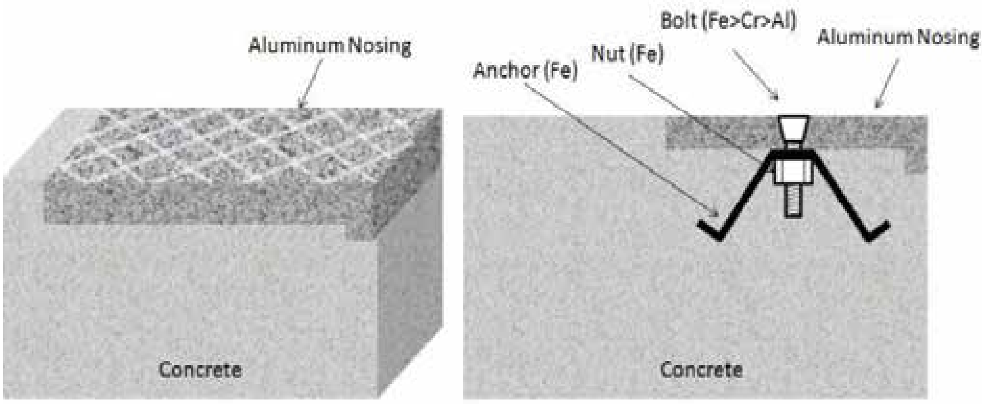
Figure 5. SEM BSE images of Al plates in hardened OPC pastes with various amounts of PAS hydrated at 3 days: (a) and (b): PC-P0; (c) and (d): PC-P3; and (e–g): PC-P6 samples.

Explanatory note. Dense and irregular hydrated aluminum oxide layers indicate volume expansion and local delamination on the metal surface.

Jana and Tepke (2009) investigated the corrosion of aluminum nosings fixed with steel fasteners on outdoor concrete stairs (**Figure 6**). Galvanic corrosion occurred where aluminum came into contact with steel, particularly in the presence of chloride ions. This resulted in significant metal loss, the nosings detaching, and the surrounding concrete cracking or spalling. The corrosion products consisted of hydrated aluminum hydroxide crystals (gibbsite, bayerite, and boehmite) and silicon-rich banded microstructures. The expansion of these products caused mechanical stress and material failure.

Figure 6

Schematic illustration showing the fixation of the aluminum nosing to concrete using a steel anchor, nut, and bolt.



Explanatory note. The figure depicts galvanic contact between aluminum and steel, which accelerates localized corrosion in the presence of chlorides.

Figure 7 shows the results of field observations of the deterioration of concrete stairs with aluminum nosings. This deterioration is primarily caused by aluminum interacting with the concrete environment's high alkalinity, moisture, and chloride ions. The resulting volumetric expansion causes the nosings to separate from the concrete surface (debonding), resulting in cracking of the concrete. Galvanic corrosion develops in areas that are in contact with steel anchors. The direct contact between aluminum and steel within the concrete accelerates corrosion in the presence of chlorides, leading to significant thickness loss of the metal beneath the nosings.

Figure 7

Field-observed deteriorations in concrete stairs with aluminum nosings.

Explanatory note. Cracking and debonding occur due to aluminum's reaction with alkaline concrete and galvanic coupling with embedded steel components.

In cases of galvanic corrosion where aluminum is coupled with steel, hydroxyl ions play a key role in the dissolution of aluminum. These ions originate not only from the concrete matrix but also from the cathodic corrosion reactions occurring at the steel surface. This dual source of hydroxyl ions significantly accelerates the corrosion of aluminum compared to scenarios without steel or without electrical coupling to steel.

Galvanic interactions between aluminum and steel result in the preferential dissolution of the more anodic aluminum, while the more cathodic steel remains preserved. Chloride ions further exacerbate this process by acting as catalysts, sustaining both the galvanic current and the aluminum corrosion. This mechanism is analogous to the use of sacrificial zinc or aluminum anodes in cathodic protection systems, where these reactive metals are intentionally corroded to protect embedded steel and extend its service life. In such systems, aluminum functions as the anode, releasing electrons that travel through the metallic pathway to the steel cathode. Meanwhile, hydroxyl ions migrate through the pore solution in the concrete toward the aluminum surface, where they react to form aluminum hydroxide.

Feldman, Clifton, and Morgan (1983) provided one of the earliest systematic investigations of aluminum behaviour in alkaline cement mortars, demonstrating that corrosion intensifies sharply above pH 13, whereas relative passivity can be sustained below pH

12.4. Experiments on various types of cement revealed that dissolution accelerated when the formation of a protective film was prevented. The authors recommend formulations supported by low pH systems or passivating additives for aluminum use in concrete. These findings suggest that the use of aluminum in concrete should be carefully considered. Comparative studies indicate that aluminum alloys such as 6061-T6 display superior resistance to atmospheric and chloride-induced corrosion compared to carbon steel; however, in highly alkaline environments dominated by $Ca(OH)_2$, aluminum shows poor durability. Luo, Li, and Xing (2022) concluded that while steel deteriorates rapidly under chloride attack, aluminum suffers severe instability in cement pore solutions, highlighting the distinct but complementary corrosion vulnerabilities of both materials. While galvanic corrosion limits direct embedding, structural innovations have opened new routes for integrating aluminum safely into composite systems.

Galvanic Corrosion and Aluminum–Steel Interaction

Apart from the corrosion of aluminum in concrete, there is a risk of galvanic corrosion, especially when it comes into direct contact with steel reinforcement or anchorage elements, which increases the risk of galvanic corrosion. In galvanic couples, aluminum is more anodic and dissolves rapidly, while steel remains protected[21]. Recent electrochemical tests in simulated pore solutions confirm this, showing that aluminum–steel couples develop significant potential differences, which lead to accelerated aluminum dissolution (Fabris et. al., 2024; Ikeuba et. al., 2024).

Galvanic corrosion is also exacerbated by the ionic conductivity of the concrete pore fluid. Hydroxide ions (OH^-), produced at cathodic sites, migrate and accelerate aluminum dissolution (Kinoshita et. al. 2013). In the presence of chlorides, thickness losses occur at an accelerated rate. Historical investigations further confirm that aluminum embedded in chloride-containing concrete undergoes significant galvanic corrosion due to moisture-mediated current paths (Pitts, 1958). To prevent these interactions, international guidelines (ISO 2022; Yao et. al., 2025) emphasize avoiding direct electrical contact between aluminum and steel by using dielectric sleeves or insulation layers. These field and laboratory findings clearly demonstrate that unprotected aluminum in concrete poses serious risks. Based on standards and recent field (Elsamak et. al., 2024; Taheri-Shakib et. al., 2024), the following checklist outlines key safety requirements for practical applications:

i. Coating requirement: Aluminum surfaces must be coated with at least two coats of bituminous paint or equivalent epoxy (Yao et. al., 2025); in early empirical reports, a bituminous coating effectively suppressed corrosion for extended periods (Zheng et. al., 2019).

ii. Coating overlap: The protective coating must overlap the concrete surface by at least 75 mm (Yao et. al., 2025).

iii. Avoidance of chloride additives: $CaCl_2$ or similar chloride additives should not be used; such additives exacerbate aluminum corrosion (Wright& Jenks 1963).

iv. Preventing direct contact with steel: A dielectric sleeve, plastic separator, or insulating mastic layer must be present between aluminum and steel (Engineering Express 2025).

v. Control of initial contact with fresh concrete: Unprocessed aluminum should not be embedded in fresh concrete, as this can result in intense hydrogen release and surface defects (Geng et. al., 2025; Runningen et. al., 2021).

vi. Evaluation of alternative binders: In special applications, binders with lower pH, such as MKPC, may be preferred (Poras et. al., 2023).

vii. Drainage and ventilation: Drainage and gas venting pathways should be provided around embedded aluminum parts to prevent hydrogen gas accumulation (Safyari et. al., 2023).

viii. Regular inspection: Surface cracks, blisters, and gas vent marks in structures where aluminum is embedded should be checked periodically (Xiao et. al., 2015).

xi. Selection of low pH systems: The use of high silica fume (up to 50%) in OPC-based mixtures reduces the pore solution pH to approximately 10.5, significantly reducing aluminum corrosion and hydrogen release (Fernández-García, 2024).

Guidance will be provided on this control list during both field applications and the design phase to ensure the safe use of aluminum in concrete.

Beyond corrosion-related concerns, recent research has also explored novel applications of aluminum in concrete. These include its role in structural composites such as concrete-filled aluminum tubes (CFAT/ATCC) and the reuse of aluminum waste as a cementitious additive. The following sections provide a detailed discussion of these applications, highlighting both their potential benefits and current limitations. For example, Liu, Wang, and Gao (2025) examined the bonding behaviour and bond-slip mechanism of concrete-filled aluminum alloy tubes (CFAT), demonstrating superior bond strength in circular sections compared to square ones and emphasising the material's advantages, such as being lightweight and recyclable, in sustainable structural design. Similarly, Al-Darraji et al. (2025) studied CFAT pile groups under combined vertical and lateral loads, demonstrating the influence of the slenderness ratio on both vertical and lateral capacity, a key consideration in foundational applications.

In terms of material reuse, research into using aluminum waste in cementitious systems is promising. Xu et al. (2023) examined the addition of secondary aluminum ash to reactive powder concrete and found improvements in Aslan (2023) tested the use of industrial metallic waste chips, including aluminum, in reinforced concrete beams and reported significant increases in flexural strength and ductility at low replacement rates.

When aluminum is coupled with steel reinforcement, galvanic corrosion accelerates aluminum dissolution. Aluminum acts as the anodic metal, while steel is cathodic. Chloride ions exacerbate this reaction, leading to rapid metal loss and concrete cracking. International codes mandate dielectric barriers between aluminum and steel to prevent such interactions.

Alternative Structural Applications: Concrete-Filled Aluminum Tubes.

Recent research has expanded the potential structural applications of aluminum in concrete systems. For example, Liu, Wang, and Gao (2025) investigated the bond-slip behaviour of concrete-filled aluminum alloy tube (CFAT) columns. They found that circular CFAT specimens exhibited significantly higher bond strength (0.77–1.77 MPa) than square ones (0.22–0.51 MPa). They also proposed a constitutive bond-slip model to predict performance. Zhao et al. (2022) studied ATCC (with circular hollow sections) under axial compression. They demonstrated that, while circular hollow aluminum enclosures provide enhanced confinement and strength potential, they are also susceptible to localised buckling depending on the thickness-to-diameter ratio.

While these findings highlight the critical influence of geometry and tube configuration on confinement effectiveness, they also reveal that aluminum's lower elastic modulus can lead to premature buckling, limiting its comparative strength against traditional steel tubes. Furthermore, current design codes, such as Eurocode 9, still lack explicit guidelines for CFAT or ATCC systems, indicating a clear need for standardisation and codification.

Use of Aluminum Waste as a Concrete Additive

In addition to structural components, aluminum waste materials have attracted attention as a partial replacement for cementitious materials. Pérez et al. (2022) investigated the incorporation of secondary aluminum chips into concrete mixes and found that low replacement levels (0.5–1.5% by weight of cement) increased tensile and flexural strength. However, higher additions (>3%) reduced workability and compressive strength, primarily due to increased porosity and gas release.

Recent studies have extended these findings. Elseknidy et al. (2020) demonstrated that incorporating aluminum dross (10% by cement mass) combined with fly ash and quarry dust enhanced both the compressive and flexural strengths of concrete mixes while maintaining workability. Conversely, Agor et al. (2023) examined the use of a blend of aluminum waste and sisal fibre in concrete. Results showed optimised flexural and compressive performance, particularly at low aluminum waste content (0.1%), which highlights the importance of precise dosage. Finally, Fathi et al. (2025) examined the use of aluminum chips and aluminum powder to create conductive concrete. Certain mixtures achieved improved mechanical strength and exhibited low electrical resistivity, opening up the possibility of using concrete for multifunctional 'heating' or de-icing applications. Overall, these findings suggest that recycled aluminum can significantly enhance the mechanical and functional properties of concrete, but only when the content and combination are optimised. It is essential to balance performance gains with durability and workability.

The evaluation of aluminum embedded in concrete environments reveals a complex interplay between material chemistry, electrochemical stability, and structural performance. Across the literature, a consistent finding is that the highly alkaline pore solution of ordinary Portland cement (OPC) (pH 12–13.5) rapidly destabilises aluminum's passive oxide layer, leading to severe corrosion, hydrogen gas evolution, and expansive corrosion products such as bayerite and gibbsite. These reactions not only degrade aluminum but also compromise concrete integrity by initiating cracks, voids, and loss of bond. Long-term studies, such as those of Herting and Odnevall (2021)[8], confirm that aluminum-containing concrete specimens develop visible cracks after prolonged exposure, while zinc samples remain largely intact, underlining aluminum's instability in conventional cementitious systems.

Conclusions and Future Perspectives

The interaction between aluminum and concrete is governed by both chemical and structural factors. In ordinary Portland cement (OPC), the highly alkaline pore solution (pH 12–13.5) destabilises the protective oxide layer on aluminum, leading to hydrogen gas evolution, dissolution, and the formation of expansive corrosion products such as bayerite and gibbsite. These reactions not only degrade the aluminum itself but also induce blistering, void formation, and cracking within the surrounding cement matrix. When aluminum is electrically connected to steel reinforcement, a galvanic cell forms, causing the aluminum to corrode faster—especially in environments containing chloride ions. International guidelines such as ACI, Eurocode 9, and the Concrete Society documents emphasize these risks and advise against embedding bare aluminum in uncured concrete. To ensure safety, they recommend applying protective coatings, maintaining electrical separation from steel, and avoiding chloride contamination during concrete preparation. These recommendations are based on consistent experimental findings showing that uncoated aluminum in OPC undergoes rapid corrosion, hydrogen release, and mechanical debonding.

Recent progress in materials science indicates that these corrosion issues can be alleviated through compositional modification. The incorporation of supplementary cementitious materials (SCMs) helps lower the alkalinity of the pore fluid and decelerates the electrochemical reaction rate. Likewise, using alternative binders, such as magnesium potassium phosphate cement (MKPC), creates a more stable and less corrosive medium, substantially limiting hydrogen release compared with ordinary Portland cement. Even with these improvements, protective surface treatments and electrical isolation from dissimilar metals remain crucial for durable performance. According to practical engineering guidance, applying proper coatings and galvanic isolation can effectively prevent dissimilar metal corrosion (URL-1). Supplementary cementitious materials (SCMs) such as fly ash, silica fume, and slag can reduce pore solution alkalinity, thereby slowing corrosion kinetics and hydrogen evolution. Alternative binders like magnesium potassium phosphate cement (MKPC) create a more benign chemical environment—lowering pH to the 8–9 range and reducing hydrogen evolution by more than an order of magnitude compared with OPC. Likewise, the application of bituminous, epoxy, or polymeric coatings, in combination with galvanic insulation, has been shown to provide effective long-term protection for aluminum components embedded in concrete.

Beyond corrosion mitigation, innovative structural and functional applications of aluminum in cementitious systems are gaining momentum. Concrete-filled aluminum tubes (CFAT/ATCC) exhibit favorable mechanical performance and recyclability when properly designed, although attention must be paid to local buckling effects due to aluminum's lower elastic modulus. Furthermore, the controlled incorporation of aluminum waste into concrete, at low dosages (<1–1.5% by weight of cement), has demonstrated improvements in flexural strength, shrinkage resistance, and multifunctionality such as electrical conductivity and de-icing potential. However, higher dosages can lead to excessive porosity and reduced compressive strength, underscoring the need for precise optimization. Taken together, the evidence presents a dual perspective. Untreated aluminum remains fundamentally incompatible with conventional OPC systems, a conclusion validated by international standards and decades of empirical data. Yet, under carefully engineered conditions, through binder modification, protective coatings, galvanic isolation, and controlled aluminum incorporation, it can be safely and effectively integrated into modern cementitious materials.

Future Perspectives: Further research should focus on developing hybrid low-alkali binders and multifunctional composite systems that permit the inclusion of aluminum without compromising structural stability. Special attention should be given to:

(i) tailoring pH-buffered cements with self-passivating additives,

(ii) designing advanced barrier coatings with self-healing or nanocomposite functionality,

(iii) employing surface treatments that improve aluminum–cement adhesion, and

(iv) expanding the recycling of industrial aluminum waste within circular economy frameworks.

(v) incorporating corrosion inhibitors into the cement matrix to mitigate aluminum corrosion.

Such advances will enable the transition toward sustainable, low-carbon, and multifunctional construction materials, where aluminum, once deemed incompatible, may serve as a lightweight, durable, and recyclable component in the next generation of eco-efficient infrastructure. Ultimately, by bridging materials science and structural engineering, the safe integration of aluminum into cementitious systems represents a key step toward sustainable infrastructure design.

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Foundations And Progress In Microscopy, Histology And Embryology

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Summary

The microscope ranks among the most important inventions in the history of science, its discovery leading to the birth and development of numerous scientific disciplines. After the light microscope was developed, it was used for a long time for curiosity and entertainment purposes. However, the microscope later became an indispensable instrument used for scientific purposes, particularly in the fields of biology and medicine, where it is utilised clinically. With the help of microscopes, a scientific 'Cell Theory' was developed, and under the influence of this theory, the scientific fields of Histology and Embryology were born and developed. As can be seen, Histology and Embryology are among the scientific disciplines that owe their existence to the microscope. During this process, many new microscopic techniques for examining tissues under the microscope found their place. In parallel, new types of microscopes were developed, primarily the electron microscope. This section focuses on the development of the scientific fields of Histology and Embryology in light of the use of microscopes. In this way, the impact of microscopes on the scientific world is evaluated against a historical background, and the effects of this impact on both the present and the future are interpreted through the lens of the disciplines of Histology and Embryology.

Microscope

A microscope is a viewing and magnifying device developed based on the principles of light and optics for the purpose of identifying and evaluating objects that cannot be seen with the naked eye. The word microscope is derived from the Greek words mikros (small) and skopos (to look, to see) (Skinner, 1949; Anonymous, 1957).

The invention of the microscope actually marks the birth of many scientific disciplines. Some scientific fields gained meaning with the invention of the microscope, while others developed rapidly thanks to it. For the sciences that use microscopes today, the period before the invention of the miCroscope is a deep darkness. Considering the point reached by microscopes today, which have been in use for over 400 years worldwide, it is evident that these devices have influenced societies not only scientifically but also socially, economically, and culturally (Armutak, 2000).

Prior to the invention of the microscope, knowledge in the biological sciences, medicine, and veterinary medicine was always obtained at the macroscopic level. After the invention of the microscope, information could only be obtained at the microscopic level, and in this way, much more detailed and surprising results were revealed. The sciences that use the microscope have developed rapidly, and in this way, the darkest secrets of nature have been illuminated by microscopes. The sciences that began their development with the microscope at their centre and have continued to do so for centuries include Histology and Embryology, Pathology, Microbiology, Virology, Parasitology, Zoology and Botany. However, Histology and Embryology have been the fields that use the microscope most extensively and intensively. This is because the microscope is the sole fundamental tool for obtaining knowledge in the field of Histology and Embryology. This discipline is a fundamental science that examines the pre-natal development of cells, tissues, and organs in living organisms, as well as their post-natal structure and function, at a microscopic level through comparative analysis (Armutak, 2000).

The microscope is essentially an optical system consisting of magnifying lenses called lenses (Wolf, 1950). In fact, the existence of glass, the fundamental element of the microscope, has been known since 4000 BC. However, for thousands of years, glass was considered merely an ornamental object. Magnifying glass, which would later be used in microscopes and called lenses, was known to the ancient Egyptians around 2500 BC. As can be seen, the history of lenses is much older than that of the microscope. It is known that glass was blown into shape in Syria in the 1st century BC and that the first transparent glass was produced there. Transparent glass then spread across Asia and Europe via Egypt and Syria. During this process, the ancient Greeks succeeded in making simple magnifying lenses using rock crystal, which they called 'Berillos' or 'Kristallos'. In the Roman Empire, in the 1st century AD, a lens was developed by filling a spherical piece of glass with water, and this lens was named after the Roman philosopher Seneca (3 BC-65 AD). Since it was possible to place Seneca's Lens in front of a light source to increase the light and spread it around, this lens is also considered the ancestor of simple magnifying glasses (Kirkpatrick, 1976; Ergin, 1997).

Ibn al-Haytham (965–1040), one of the scholars of the Islamic civilisation era, conducted research on the magnifying properties of lenses, and his views influenced many Western scientists who worked on microscopes and telescopes. One of these Western scientists was the renowned English philosopher Roger Bacon (1214–1294). Bacon added to the book of the aforementioned Islamic scholar, provided practical interpretations, and was also the first to propose the idea that lenses could be used as spectacles (Sarton, 1950; Bradburry & Turner, 1967).

Again, during the Islamic Civilisation era, it was determined that writing appeared larger when viewed through a lens, and lenses were used like magnifying glasses, equipped with frames and handles, to enable those with poor eyesight to read. These early lenses were again made from transparent stones, particularly beryl, rather than glass. Some time later, separate lenses were made for each eye and placed in a frame, creating the first spectacles (Bernal, 1995). The first silicate glass was produced in Italy in the 13th century, and in the 14th century, lenses began to be used as spectacles and quickly became widespread. Salvino d'Armato degli Armati is credited as the inventor of spectacles. However, it is still not known for certain who first used spectacles. Nevertheless, it is known that ordinary magnifying glass-like lenses were used for reading or entertainment purposes (Dobell, 1960).

The Invention of the Microscope and the First Microscopists

The question of who invented the microscope and where it was invented has always been a subject of debate. It is thought that the microscope was first invented in Holland. This is because jewellery crafting techniques were highly developed in this country. Jewellers, who also crafted lenses to make spectacle lenses, may have led to this result. The Zacharias family, who lived in Middelburg, Holland, and were spectacle makers, were pioneers in this field. Zacharias Jansen, a member of this family, was working with lenses in water to make spectacles in the late 16th or early 17th century, when he noticed that a combination of a pair of convex and a pair of concave lenses magnified objects in water. In this way, he developed the first compound microscope by chance (Wolf, 1950; Dobell, 1960; Purtle, 1974). Until then, only the magnifying properties of a single convex lens had been utilised, but Zacharias Jansen laid the foundation for the first compound microscope by placing two convex and two concave lenses inside a tube. Galileo Galilei also took advantage of this discovery and succeeded in developing the binoculars, telescope and microscope (Uzluk, 1959; Boorstin, 1996; Merdivenci, 1975).

Shortly after the invention of the telescope, people began using this device to magnify small objects in their vicinity. Even Galileo Galilei used his telescope like a microscope (Boorstin, 1996). While microscopes were being produced in Holland in the first decade of the 17th century, a new form was independently developed in Italy (Dobell, 1960). Developed by Jansen, these microscopes, capable of magnifying an object nine times, became one of the most popular devices of the period and were even sold to the Dutch Royal Family. The fame of the microscope quickly spread from the Netherlands throughout Europe, and the number of microscope makers increased rapidly. One of these new microscope makers, Cornelius Van Drebbel, developed a new microscope model in London in 1619, with two convex lenses at one end and a concave objective at the other (Wolf, 1950; Erbengi, 1988; Eren, 1996).

The Use of the Microscope for Biological Observations

The microscope was also used for biological observations by Galileo Galilei in 1610 or earlier. Galileo Galilei examined the sensory and locomotor organs of small animals and the compound eyes of insects; by making some modifications to the microscope developed by Drebbel, he ensured that the device could be used both as a microscope and a telescope. The Italian word 'Occhialino' and the Latin word 'Perspicillum' were used at that time to mean both telescope and microscope (Wolf, 1950; Boorstin, 1996). Giovanni Faber, a physicist and natural scientist who was one of the first members of the Lincei Academy, used the word 'Microscopio' (microscope) for the first time in history in a letter he wrote to his friend Federico Cesi on 13 April 1625. In his letter, Faber stated: 'After the model of the telescope, I thought of calling this invention "microscope", because this instrument allows us to perceive the images of very small objects' (Dobell, 1960; Boorstin, 1996). Federico Cesi and members of the Lincei Academy were among the scientists who played a very active role in these early microscopic investigations (Mettler, 1947). Also in 1625, Italian researcher Francesco Stelluti published his book 'Apiarium,' in which he used the microscope for scientific purposes and drew detailed illustrations of the head and mouth parts of bees. Stelluti stated in his work that he used the microscope to examine the body parts of bees (Wolf, 1950; Westfall, 1987; Lyons & Petrucelli, 1987). The first medical study based on the microscope was the work entitled 'Historiarum et Observationum Medicophysicorum' published in 1653 by the French physicist and philosopher Pierre Borel (1620–1689). Although Borel mentioned creatures resembling whales or dolphins floating in blood in 1655, he also described one of the earliest examples of a compound microscope. The first microscopes were quite simple and could only magnify objects 100–200 times (Dunlop & Williams, 1996).

Leeuwenhoek and the Golden Age of Microscopic Observation

Antony Van Leeuwenhoek (1632–1723), a Dutch merchant and self-taught scientist, was one of the most remarkable figures in 17th-century biology and one of the most important early microscopists. In his spare time, he made lenses for microscopes, and the lenses he produced continued to be influential until the 19th century. Although he could not directly follow contemporary scientific publications because he did not know Latin, his extraordinary powers of observation and diligence enabled him to make numerous independent discoveries. He made 247 microscopes and 419 lenses from precious metals such as gold and silver; using two small concave lenses together, he created his best microscopes, which could magnify objects approximately 270 times (Ünver, 1943; Dobell, 1960; Lyons & Petrucelli, 1987). Leeuwenhoek did not actually use a compound microscope in the modern sense, but rather simple lens systems. He placed a lens on a flat silver or brass plate and used a concave mirror to focus the light onto the object (Wolf, 1950; Dobell, 1960). Before his death, Leeuwenhoek sent some of his microscopes and observation reports to the Royal Society in London; these studies were published, and he was elected a member of the Royal Society in 1680 (Uzluk, 1959). In 1674, Leeuwenhoek observed spermatozoa, protozoa, and bacteria under the microscope for the first time and named them 'Animalcules', meaning 'tiny animals' (Ünver, 1943; Uzluk, 1959; Dobell, 1960; Ural, 1998). He also examined human skin, tongue papillae from oxen, lens crystalline and urinary bladder, pig liver, hair structures of various animal species, and the microscopic anatomy of insects (Dobell, 1960). He was the first to correctly identify the blood cells that Malpighi had described as 'fat globules'; he noted that the erythrocytes observed by Swammerdam were round in mammals and oval in fish and amphibians. Leeuwenhoek, who also examined rainwater and dental plaque under the microscope, was the first to show skeletal muscles under the microscope, defining the striated structure of muscles; he discovered capillaries in the tail of a frog tadpole, demonstrating the connection between arteries and veins. He thus supported Malpighi's views on the circulatory system (Ünver, 1943; Wolf, 1950; Uzluk, 1959; Erbengi, 1988).

Dutch physician Jan Swammerdam (1637–1682) studied insects and small creatures, performing extremely delicate dissections under the microscope. In 1658, Swammerdam observed frog erythrocytes for the first time and prepared his work Bibel der Natur, in which he drew detailed illustrations of the internal organs of insects. In his studies, Swammerdam injected coloured liquids into insects to enhance the visibility of their organs (Wolf, 1950; Uzluk, 1959; Ünver, 1943; Erdemir, 1994). Italian physician and professor of physiology Marcello Malpighi (1628–1694) was one of the scientists who used the microscope most effectively in his research. Malpighi examined plants and insects under the microscope and identified structures in organs such as the kidney, spleen, liver, and skin that would later be called 'Malpighi bodies' (Wolf, 1950; Erk, 1978). Malpighi developed new methods for preparing tissues to be examined under the microscope (Lyons & Petrucelli, 1987). Due to his work in the field of histology, considered the 'sister science' of pathology, Malpighi is recognised as the 'Founder of Biological Microscopy' (Long, 1965). Leeuwenhoek, who made significant contributions to the accumulation of biological knowledge, is also considered one of the 'Founders of Histology' alongside Malpighi (Westfall, 1987; Boorstin, 1996; Theodorides, 1993). Johannes Hevelius (1611–1687), who lived during the same period, developed the 'micrometre' screw used for fine adjustment in microscopes in 1673 (Erbengi, 1988).

The Birth of Cell Theory and the Formation of Histology

Following these developments, new microscopists emerged in England. The earliest and most famous of these was the botanist Robert Hooke (1635–1703) (Wolf, 1950; Purtle, 1974). Hooke's early scientific work was based entirely on microscopic observations, demonstrating how effective the use of microscopes could be in scientific research. In his famous work Micrographia, published in 1665, Hooke first used the term 'cellula' (cell), meaning 'air-filled cavity'. Using a compound microscope with limited magnification power, he examined seedless, honeycomb-shaped fungal cells and named them 'Cellula' (Cell). In his work, he included 57 remarkable microscopic images of plants and insects, accompanied by his own drawings (Wolf, 1950; Sencer, 1998). While Leeuwenhoek and Malpighi worked with simple lenses, Hooke used one of the most advanced examples of a compound microscope. Hooke's microscope is a system in which the object to be observed is fixed with a needle protruding from the base, screwed onto a movable platform, and light is provided by a lamp with a spherical condenser (Wolf, 1950). Hooke increased the clarity of the image by adding a third lens, which he called the 'middle glass,' in addition to the objective and eyepiece lenses (Ergin, 1997; Wolf, 1950). Furthermore, in 1678, Hooke dipped the objective lens in water, thereby testing the 'wet immersion' technique for the first time and succeeding in improving image quality (Erbengi, 1988). Hooke's Micrographia became the most renowned work in this field. Hooke's descriptions of the structure of fungal cells, his observations of eels in vinegar, his studies of insect anatomy and various small objects were enthusiastically pursued by subsequent microscope users (Wolf, 1950). However, Hooke failed to grasp the significance of his observations, and as a result, the 'Cell Theory' was only proposed in the 19th century by Rudolf Virchow (Uzluk, 1959).

The first person to use a microscope in disease research was the physiology professor Athanasius Kircher (1602–1680). In 1646, Kircher claimed to have observed plague microbes in blood using a simple microscope with a low-power lens at one end and a flat glass plate at the other, but his claim was met with scepticism (Wolf, 1950; Lyons & Petrucelli, 1987). Similarly, Schelftrateus, an official at the Vatican Library, published an illustrated study on the use of the microscope in medicine in the 1680s (Mettler, 1947). Simple microscopes were mostly used for examining insects, which is why they were referred to as 'flea glasses' or 'fly glasses' at the time (Wolf, 1950).

However, despite the more intensive use of microscopes from the 17th century onwards, this invention did not influence the medicine of the period (Erk, 1978). The physicians of the time remained indifferent to the microscope and the discoveries made with it, continuing to practise their art traditionally. Consequently, no significant progress was made throughout the 18th century towards the scientific definition of the cell. However, at the end of the century, Marie François Xavier Bichat (1771–1802) realised, without using a microscope, that organs were composed of tissues and proposed that there were 21 different tissues in the body. Bichat likened these tissues to a ‘spider’s web’ or ‘cloth weave’ and used the term “tissu” (tissue) for the first time. Thus, the concept of ‘histology,’ derived from the Greek word ‘histo’ (spider’s web or cloth weave), was born. Bichat demonstrated that diseases affect the vital properties of tissues and is therefore recognised as the ‘Founder of Modern Histology’ (Erk, 1978; Şan, 1994; Theodorides, 1993). However, due to optical errors in the lenses at that time, the magnification power of microscopes remained limited (Karasszon, 1988). Although Bichat did not give the microscope the importance it deserved, the microscope has now become an indispensable tool in biological research (Long, 1965). G. Hertel (1683-1743) began using a flat mirror for light in microscopes in 1716, and in 1738, J. N. Lieberkühn (1711-1756) developed and began using a ring-shaped mirror. John Cuff (1708-1772) worked on a microscope with a sliding stage (carriage) and a fine adjustment knob (micrometer) in 1738, while George Adams developed a microtome for sectioning in 1770, and J. Bleuler (1757-1829) used a condenser assembly capable of moving focus in the 1780s. Meanwhile, J. N. Lieberkühn injected a coloured substance into blood vessels in 1748 to achieve staining in tissues and described the ‘Lieberkühn Glands’ in the intestines, which are named after him (Erbengi, 1988).

Robert Brown (1773–1858) was the first to identify the nucleus in plant cells and named it the ‘nucleus.’ Anatomy professor Jacob Henle (1809–1885) built upon the foundations of histology laid by Bichat, introducing new structures. Henle defined the cellular structure of tissues, establishing ‘microscopic anatomy’ based on cytology, and proposed that living organisms could only be formed by living cells. Henle demonstrated the presence of smooth muscle in the middle layer of arteries, the ‘Henle Layer’ in hair follicles, the ‘Henle Loop’ in the kidneys, the connections of the hippocampus in the brain, and the character of the posterior lobe of the pituitary gland. He provided the first accurate histological description of the corneal layer of the eye, studied the urinary bladder, and also focused on the development and structure of the larynx, introducing the term ‘epithelium’ for the first time (Mettler, 1947; Dunlop-Williams, 1996). Henle also published his books entitled ‘Allgemeine Anatomie’ in two separate editions in 1837 and 1841, and ‘Handbuch der Systematischen Anatomie des Menschen’ in three volumes between 1856 and 1873. These books contain illustrations of the macroscopic and microscopic structure of the entire body, an excellent classification of tissues, and a history of descriptive microscopy and histology (Mettler, 1947; Uzluk, 1959; Lyons-Petrucelli, 1987). It has been argued that Henle’s histological findings were more significant than those of the renowned anatomist Vesalius (Long, 1965).

Biologist Matthias Jacob Schleiden (1804–1881) succeeded in establishing the concept of the plant cell and, in doing so, conducted microscopic studies on plants, focusing on plant cells and their reproduction. He determined that the nucleus is naturally present in flowering plants and demonstrated the nucleolus (Theodorides, 1993). Accepting that the cell produces its own similar form through a process similar to crystallisation in chemistry, Schleiden examined cells in different parts of both angiosperms and gymnosperms, stating that the cell is the smallest independent unit in living organisms, that it exists in harmony with the entire structure, and that it performs its assigned tasks within the organism (Tekeli et al., 1999).

Influenced by Schleiden's views, Theodor Schwann (1810-1882), who accepted his ideas on plant cells and attempted to adapt them to animal cells, stated that he aimed to demonstrate that even the most complex animal tissues are composed of cells. In 1839, Schwann published his famous book 'Mikroskopische Untersuchungen' (Microscopic Investigations), which revealed the microscopic structure of plants and animals. In this book, the cell was accepted as the basic unit of life, and this theory revolutionised biology, leading to the emergence of modern concepts related to embryology, genetics, and evolution (Theodorides, 1993). Schwann defined the 'Schwann Cells' named after him in the nervous system and also discovered the striated muscle structures in the upper part of the oesophagus (Mettler, 1947). Schwann, who conducted detailed research on cells, summarised his work as follows: "All plants and animals are composed of cells. Cells have an individual life. Cells have their own unique lives and perform specific functions within the whole" (Tekeli et al., 1999).

Schwann's 'cell theory,' which posits that the animal body is composed of cells that have been specially modified for specific purposes or of substances formed by these cells, remains valid today. By studying animal cells on chicken eggs and observing their developmental stages, Schwann classified tissues into five groups based on his findings (Tekeli et al., 1999).

1-Cells that are separate from each other, such as blood cells.

2-Cells that are arranged side by side, such as skin cells.

3-Cells that are needle-shaped, such as muscle cells.

4-Cells whose cell membranes have thickened and hardened, such as bone and cartilage cells.

5-Cells whose cell membranes and spaces are adjacent to each other, such as nerve cells.

Although the development of cell theory is associated with Schleiden and Schwann, René-Joachim-Henri Dutrochet (1776-1847) surpassed these researchers in many respects. At least 15 years before Schwann's work, Dutrochet focused on the role of the cell as a physiological unit, pointing out that the basic unit in plant and animal tissues was the cell, observing that dead structures such as hairs were actually composed of living cells, proposing that growth was dependent on the formation and development of new cells, discovered migrating leukocytes, and first used the term 'osmosis' (Mettler, 1947).

Apart from Schwann, many scientists during his time and afterwards conducted research on cells and determined the properties and physical and chemical characteristics of the cell nucleus, membrane and protoplasm. The main focus of research on the nucleus has been on 'cell division'. Thanks to these studies, research on mitosis, amitosis, and meiosis yielded results at the beginning of the 20th century. Similarly, studies on protoplasm made it possible to determine the chemical building blocks of living organisms, thereby making the structure of living organisms more understandable. These studies ensured that the subject of cells took shape as an independent field of research within biology (Tekeli et al., 1999).

The current understanding of cells is the product of observations made by various scientists who lived in the 19th century and conducted studies using microscopes, and some of these scientists contributed to the formulation of cell theory (Theodorides, 1993). One of the first to suggest that organs must be composed of cells, the Czechoslovakian scientist Johannes Evangelista Pürkinje (1787-1869) first became closely interested in the living entity of the cell in 1837 or 1839 and named it 'protoplasm' (Mettler, 1947; Theodorides, 1993; Dunlop-Williams, 1996). Pürkinje was also the first researcher to use the 'microtome' for sectioning and 'Canada balsam'. Pürkinje, who also discovered the sweat glands in the skin, defined the 'Pürkinje Cells' in the cerebellum, named after himself, and the 'Pürkinje Fibres' in the heart muscle and uterus (Mettler, 1947). Pürkinje, who also used new achromatic lenses that yielded good results under the microscope, put forward his hypothesis showing the functional hierarchy between nerve cells, which could form a stepping stone for the 'Neuron Theory' (Dunlop-Williams, 1996).

The anatomist Max Johann Sigismund Schultze (1825–1874), who worked on cells and whose research was almost entirely histological, was the first to correctly define the cell in 1854, stating that 'the cell is a small mass of protoplasm containing a nucleus and surrounded by a rigid cell membrane.' He conducted successful studies on nerve endings in sensory organs and on the nose and retina. Schultze, who also developed the tissue staining technique using osmic acid, founded the journal 'Archiv für Mikroskopische Anatomie' in 1865 and served as its editor until his death (Mettler, 1947; Dampier, 1957; Theodorides, 1993). Rudolf Wagner (1805-1864) also conducted detailed studies on nerve cells in the brain of the electric fish (Mettler, 1947). The resulting understanding of cells soon had a profound impact on histology and embryology studies (Erk, 1978).

Rudolf Virchow (1821-1892), a student of Johannes Müller (1801-1858), one of the first to use the microscope in pathology, reported that all vital events and disease symptoms occur in the cells that make up the body, and conducted research on the phases of karyokinesis. Virchow also opposed the view previously put forward by Schwann, concluding that cells are not formed in tissue fluids but are the product of division. In his book ‘Cellular Pathologie’, published in 1858, Virchow summarised his view as ‘omnis cellula e cellula’, meaning ‘every cell originates from another existing cell’ (Mettler, 1947; Dampier, 1957; Lyons-Petrucelli, 1987; Theodorides, 1993).

In plants, cell division was demonstrated in the true sense in 1875 by the German botanist E. Strasburger (1844-1912), who observed mitotic division in plant cells and the division of the cell into two parts that could be stained. Another German physician, W. Flemming, demonstrated mitosis in diploids and further deepened and explained his research by studying the phases of karyokinesis, as did Virchow. Flemming named the stainable particles of the nucleus ‘chromatin’ (Mettler, 1947; Theodorides, 1993). Wilhelm Waldeyer (1836-1921) named the structures he observed in cell nuclei ‘chromosomes’ in 1891 and the cells found in the nervous system ‘neurons’ (Mettler, 1947; Lyons-Pettrucelli, 1987).

One of the leading microscopists of his time was the Swiss scientist Rudolph Albert von Koelliker (1817–1905). He made countless contributions to histology, embryology, and morphology. His work demonstrated that spermatozoa originate from testicular tissue. Further detailed Henle’s studies on the muscle structure of blood vessels, made observations on neuroanatomy, and wrote the first organised histology textbook, Mikroskopische Anatomie, in light of the new cell theory (Mettler, 1947; Lyons-Petrucelli, 1987). Published in Germany in 1851, this first histology textbook in the world also covered the details of the nervous system, the smallest structures of the eye and ear, and the importance, functions, and classifications of various types of blood cells. Koelliker’s histology textbook was translated into English in 1852, and the tissue and organ diagrams included in both language editions are still noteworthy today (Carleton-Short, 1954).

Researchers who studied the microscopic details of the nervous system in laboratories and demonstrated staining methods for nerve cells and their filaments have greatly benefited clinical neurology. One of the pioneers of this movement, Camillo Golgi (1844-1926), first isolated nerve tissue cells in 1873 using silver nitrate. Another Spanish researcher working in the field of neurohistology, Santiago Ramon Y Cajal (1852-1934), together with Camillo Golgi, used the metal impregnation method in neurohistology and won the 1906 Nobel Prize for their findings obtained from the central nervous system (Uzluk, 1959; Erbengi, 1988). Furthermore, the experimental principles of nerve cell degeneration developed by Auguste-Henri Forel (1848-1931), who also worked on neurohistology, replaced the old views on this subject (Mettler, 1947).

Russian scientist Elie Metchnikoff (1845-1916) drew attention to the fact that certain cells in the body eliminate foreign particles and microorganisms by ingesting them, and named these cells ‘phagocytes’. Consequently, by distinguishing between ‘macrophages’ and ‘microphages’ in blood and tissue cells, he laid the foundation for the cellular theory of immunity (Dampier, 1957; Erk, 1978). Meanwhile, the renowned physician Joseph J. Lister (1827-1912) developed a modern type of compound microscope with an achromatic objective (Long, 1965). Furthermore, in 1907, H. Harrison conducted important studies on tissue culture (Erbengi, 1988; Karasszon, 1988).

Following the formulation of cell theory, the development of cytology continued with the emergence of new techniques, enabling the acquisition of tissues that could be cut into thin sections using microtomes and stained with various substances such as plant dyes and mineral salts. The impact of cell theory on biology has been immense (Theodorides, 1993).

Microscope Errors and Their Correction

From the outset, all microscopes produced have been affected by chromatic and spherical aberrations (deviations), leading to misinterpretations. Newton, in particular, conducted important work on eliminating these aberrations (Merdivenci, 1975; Boorstin, 1996). Chromatic aberration arises when each colour, which makes up white light and has a different wavelength, is refracted at a different angle as it passes through the lens and converges at different focal points. As a result, a coloured halo forms around the image. Spherical aberration, on the other hand, arises from the lens thickness not being the same at the edges and the centre. As rays pass through thick and thin areas, they exhibit different refraction properties and converge at different focal points. Consequently, the image field cannot be completely sharpened (Artan, 1988).

By conducting research specifically aimed at eliminating chromatic aberration, work began on developing the achromatic lens in 1807 by H. Deijel (1738-1809) J. L. V. Chevalier (1770-1840) and C. L. Chevalier (1804-1859) in 1824, and Giovanni Battista Amici (1786-1863) in 1829.

Andrew Ross (1798-1859) and his son Thomas Ross (1819-1870) produced the first classical binocular microscope in 1862 (Merdivenci, 1975). Despite the research conducted by the ‘Oberhauser’ and ‘Hartnack’ companies, no progress was made in eliminating chromatic aberration until Ernst Abbe (Karasszon, 1988). However, Ernst Abbe (1840-1905) and Carl Zeiss (1816-1888) successfully used the apochromatic objective lens they developed to eliminate spherical and chromatic aberrations for the first time in 1886. In this way, they achieved technical perfection in magnification by eliminating both spherical and chromatic aberrations and improved the eyepieces and objectives. Ernst Abbe also completed his development work on the condenser, one of the most important parts of the microscope, in 1873, and in 1878, together with Carl

Zeiss, used the first homogeneous oil immersion lens (Long, 1965; Merdivenci, 1975; Erbengi, 1988; Karasszon, 1988).

The Development of New Microscopic Techniques

Joseph Janvier Woodvard was the first to investigate the possibilities of taking photographs under a microscope in 1883-1884, and is therefore considered the 'pioneer of microphotography'. Moritz V. Rohr (1868–1940) also conducted research in the field of microphotography in 1904 (Merdivenci, 1975). Meanwhile, in 1887, H. S. Greenough made significant contributions to the development of the binocular microscope (Erbengi, 1988).

Advances in histological techniques by researchers have enabled the discovery of productive and unexplored microscopic areas. General histological practices in the 19th century were based on the immediate examination of frozen fresh tissue sections cut with a razor. All tissues except cartilage and bone are too soft for sectioning, making it extremely difficult to obtain sections from them. This difficulty could only be overcome by freezing the tissues to be sectioned. The general method consists of placing the cut material in a container and immersing it in a freezing saltwater mixture. After a short time, the tissues can be easily cut with a razor. Pieter de Riemer (1760-1831) from the Netherlands was one of the first to use this method. Benedict Stilling (1810-1879) successfully used the freezing method, particularly in his classic studies on central nervous system histology (1843). Later, physiologist Gabriel Gustav Valentina (1810-1883) discovered double-edged blades and used them to obtain thin sections from tissues (Mettler, 1947; Long, 1965).

Work on microtomes gained momentum towards the end of the 19th century, and French-made microtomes, in particular, became more popular due to their simplicity and affordability. Numerous scientists working at universities developed new and improved forms of microtomes, while the mechanical details of microtomes were perfected by technical staff at universities. A new microtome invented by German pathologist Richard Thoma, which served as a model for much more modern microtomes, came into use from 1881 onwards (Long, 1965).

Particularly from the mid-19th century onwards and in parallel with these developments in light microscopy and microscopy techniques in the 20th century, entirely new methods and techniques were developed and began to be used in the field of histology. In this way, significant advances were made in cytology, histology, and microscopic anatomy. Meanwhile, numerous newly synthesised chemical substances began to be used in histology laboratories. The vast majority of these methods are staining techniques used to determine the presence of tissues and cells. Microscope techniques, which have advanced over time, have become the most important part of the discipline of microscopic anatomy and have formed a fundamental infrastructure for histochemical research today. These developments in histology were naturally and rapidly applied in the field of pathology as well (Long, 1965; Pearse, 1968; Lyons-Petrucelli, 1987).

Danish scientist Adolf Hannover (1814-1894) used chromic acid solutions to fix tissues, and German physicist F. Blum used formaldehyde as a fixing solution in 1893. In addition, Carl Kayserling and Rudolf Virchow jointly developed the 'Kayserling Solution' in 1897, which was used for fixing and preserving large tissue specimens. In 1894, Konrad Zenker developed the 'Zenker Solution,' which contained potassium dichromate and mercuric chloride. Tissues to be embedded in paraffin require solidification and dehydration, so alcohol has long been used for this purpose.

Salomon Stricker used a mixture of beeswax and oil for embedding, while Edwin Klebs, in 1869, first described the method of embedding tissue in paraffin and used this method in his own laboratories a few years later. Matthias Duval (1844-1915) first developed collodion, and shortly afterwards, its commercial form, 'Celloidin', was introduced to the market and is now used in conjunction with paraffin. Transparent solutions of carmine and gelatin were first injected into tissue vascular systems in 1847 by Joseph Gerlach (1820-1896). This was one of the first significant staining procedures. Alum-Haematoxylin, a nuclear stain still used today, was first used by F. Böhmer in 1865. The discovery of aniline dye created great opportunities in staining. Furthermore, Paul Ehrlich played a major role in this field and proved through his work that living tissues could also be stained with a group of dyes (Long, 1965). However, at the beginning of the 20th century, histology was not limited to the examination of normal tissues; it also focused on studies aimed at understanding the cellular basis of pathological changes. The staining methods used during this period became a fundamental tool not only for distinguishing tissue types but also for diagnosing diseases. In this context, Haematoxylin-Eosin (H&E) staining began to be used as the standard method for evaluating the general morphology of tissues. Additionally, special methods such as Van Gieson, Masson Trichrome, PAS (Periodic Acid-Schiff), and Sudan stains have been developed; it has become possible to selectively demonstrate different cellular components such as connective tissue, muscle, fat, and carbohydrate content, by staining them. The widespread use of these techniques has transformed histology from a morphological field into a diagnostic and analytical science.

The Development of New Microscopes and Modern Histology

The limitations of the light microscope became even more apparent in the mid-20th century, resulting in a need for higher resolution images. This requirement led to the development of the electron microscope in the 1930s. Electron microscopes, which use electron beams instead of light beams to make invisible living or non-living entities visible, were developed and began to be used in the first half of the 20th century.

Numerous researchers, chief among them K. F. Braun (1850–1918) and J. J. Thomson (1856–1940), conducted studies on cathode rays and the relationship between cathode rays and electrons in the final years of the 19th century. The concept of the electron microscope originated with the 'Wave Mechanics Theory' (1924) of the world-renowned French physicist Louis de Broglie (1892-1987). The most significant difficulty encountered in research on electron microscope optics was the ability to form an image with electrons. This problem was solved, in particular, by adapting Abbe's views on image formation in optical microscopes to the electron microscope, and only then was it possible to achieve rapid progress in the construction of electron microscopes (Bradburry & Turner, 1967; Larsen, 1975; Erbengi, 1988).

Meanwhile, Hans Busch's discovery in 1926-1927 that an electromagnetic field deflects electron beams constituted an important step in the construction of the electron microscope. As a result of systematic work in this direction, the renowned physicists Max Knoll (1897) and Ernest Ruska (1906-1988) established the basis for the first electron microscope in 1931. Approximately one year later, in November 1932, the first electron microscope was built in Berlin and entered service in 1933. The first biological research using an electron microscope was conducted in 1934 (Bradburry & Turner, 1967; Larsen, 1975; Merdivenci, 1975; Erbengi, 1988). Tissue sections of sufficient thinness for electron microscopy were first obtained by Von Ardenne in 1939. Latta and Hartmann were the first to use glass blades in 1950 (Reid, 1970). Ernest Ruska, who invented the electron microscope in 1933, won the Nobel Prize in Physics in 1986, and his first reaction to this event was to say, 'I am very happy. I thought I had been forgotten' (Erbengi, 1997).

Thus, the detailed structure of organelles such as mitochondria, ribosomes, endoplasmic reticulum, cell membrane, and nucleolus could be observed for the first time with the electron microscope. The electron microscope revolutionised cell biology and histology, providing molecular-level explanations for morphological information. With this development, histology redefined itself as a molecular morphology science that studies the structure and function of living tissues at the microscopic level, independent of anatomy.

Additionally, the Ultraviolet Microscope, which allows for the examination of cellular elements that absorb ultraviolet rays, such as nucleic acids, was developed in 1903 by R. Zsigmondy and H. Siedentopf in 1903, the Polarisation Microscope, which can examine double-refracting materials, was developed by W. J. Schmidt in 1924, the Fluorescence Microscope was developed by Carl Reichert in 1911, and the first Phase Contrast Microscope, which can examine living, moving materials, was developed by

Fritz Zemnike in 1932. In addition to all these, the Confocal Microscope was developed starting in the 1980s and, thanks to its optical sectioning feature, made it possible to examine the three-dimensional structure of tissues at high resolution. This microscope has enabled the detailed examination of neural networks, vascular structures, cytoskeletal organisation, and intracellular transport mechanisms in modern cell biology (Erbengi, 1988; Karasszon, 1988). Finally, the cryo-electron microscope began to be used in the 21st century as a microscope that allows the atomic-level examination of proteins, viruses, and macromolecular complexes in their natural state. Here, samples are rapidly frozen with liquid nitrogen and imaged in an electron microscope before ice crystals form. This method enabled the observation of cell structure without damage and earned researchers Jacques Dubochet, Joachim Frank, and Richard Henderson the Nobel Prize in Chemistry in 2017.

Thus, histology has evolved beyond being merely a discipline that studies cell and tissue morphology since the mid-20th century; today, it has become a multifaceted field of research that integrates with biochemistry, molecular biology, and genetics. During this process, rapid advances in microscope technology have enabled the study of the three-dimensional, dynamic and functional structures of living cells. At the same time, these developments have enabled microscopic-level investigations in cell biology and have brought histology closer to physiology (histophysiology) and molecular biology.

These developments have transformed histology from merely the ‘structural examination of tissues’ into a discipline that unravels the dynamic organisation of living systems. Thus, modern histology has elevated itself to the status of a scientific discipline that pioneers the understanding of life at the microscopic level by integrating morphology with molecular biology, genetics, biochemistry, and biophysics.

Embryology

The Origins of Embryology

People have been interested in embryonic development since ancient times. In antiquity, embryological studies were conducted in Ancient Egypt, Babylon, Assyria, and India. It is known that embryological studies were particularly well developed in India. In India, Susruta, in the 6th century BC, proposed that the embryo was formed from semen and blood, and that the origin of these two was a white fluid found in the intestines. He focused on the development of the child in the womb according to months and reported that the soft parts of the body came from the mother and the hard parts from the father. In Egypt, systematic embryology studies were conducted, and artificial incubators were developed for bird eggs. Similarly, artificial incubation was successfully applied in China (Needham, 1934).

Embryology in Ancient Greek Science

Later data on embryology can be found in ancient Greek. Alcmaeon, Hippocrates, Empedocles, and Aristotle contributed to knowledge on this subject (Petorak, 1988; Kayalı, 1989; Theodorides, 1993). Hippocrates (460-377 BC) proposed that the embryo was nourished by the mother's blood, which flowed towards the foetus, coagulated there, and shaped the embryo's flesh. He stated that the white part of the bird's egg is edible, while the yolk is used for structural purposes in the body. Parmenides (540-450 BC) reported that the female embryo forms on the right side of the body, while the male embryo forms on the left side (Needham, 1934).

Aristotle (384–322 BC) observed chick development from the earliest days in the egg, investigated the early development of the heart and major blood vessels, examined the first heartbeats of the embryo, and ultimately advanced thinking on circulation, thereby creating an advantage for those who came after him (Smithcors, 1958). Aristotle proposed that the heart was the first organ to differentiate, that foetuses did not breathe, and that male and female embryos did not develop in different parts of the uterus (Needham, 1934; Lyons-Petrucelli, 1987).

One of his most notable works is his research tracking placental development in sharks. Aristotle also observed the development of fish and emphasised the similarities between fish and placental mammals (Singer-Underwood 1962). Aristotle was the scientist who grouped animals into three embryological groups: 'oviparous' (those that hatch from eggs), "viviparous" (those that give birth to live young), and 'ovo-viviparous' (those that hatch from eggs and give birth to live young). Similarly, he also conducted studies based on comparative observations of the reproduction and development of vertebrates and invertebrates (Bertier-Aristot, 1998). Aristotle is recognised as the 'Founder of Embryology' due to these early and important works in the field of embryology (Kayalı, 1989). Aristotle reported that the germ (seed) is formed from the mixture of male and female reproductive fluids, and thus the spirit from the male and the body from the female shape the foetus (Sarton, 1950). Aristotle theoretically indicated that the new life formed within the female organism, suggesting that all reproductive material came from the female and stating that the reproductive materials in the female were contained within the menstrual blood, which was released at intervals (Sarton, 1950; Erk, 1978; Petorak, 1988).

Herophilus (375–280 BC) described the ovary and oviduct, while much later Galen (129–199 AD) reported that a fluid formed in the female's ovaries was transported to the uterus, where it mixed with the seminal fluid to result in pregnancy. Contrary to Aristotle, he proposed that male seed was both the material and the cause of reproduction (Petorak, 1988). Galen, who conducted more detailed embryological studies, also provided anatomical descriptions of the allantois, amniotic membrane, placenta, and membranes. According to Galen, embryonic life consisted of four stages: 'the unformed seminal stage, the stage in which the brain, heart, and liver are formed, the stage in which all organs are formed, and the stage in which the formed organs are clearly visible'. Parallel to these developments, Galen also proposed that the embryo transitions from the life of a plant to the life of an animal (Needham, 1934).

Embryology in the Middle Ages and the Modern Era

During the Middle Ages, theological theories were also developed concerning embryonic development and the formation of life (Sarton, 1953). Furthermore, in the baytarnames written during the Islamic civilisation, the foetal development of young animals in the womb was frequently discussed (Dinçer, 1973). Throughout the Middle Ages and until the early 17th century, the views of Aristotle and Galen generally remained dominant in the field of embryology. During this period, two important embryological works by physicist and anatomy professor Hieronymus Fabricius d'Aquapendente (1533-1619), who inherited the legacy of Leonardo Da Vinci's (1452-1519) studies and drawings, stand out in the field of embryology in the 1600s. His first book, 'De Formatione Ovi et Pulli,' which describes chick development, is considered to be in line with Aristotle and Galen's views. His second work, 'De Formatio Foetus', covers domestic mammals as well as mice and sharks (Dunlop-Williams, 1996). In addition, research prepared by Pierre Belon of Le Mans (1517-1564) in 1551, showing the characteristic mammalian foetus in the uterus, was published.

As can be seen, the 17th century did not inherit a unified and common theory of reproduction from the Old World. Different theories exist for each class of living beings. It is clearly evident that reproduction in mammals differs from that in oviparous animals. The first research attempting to provide a common explanation for the reproduction of all animals was conducted by Doctor of Medicine William Harvey (1578-1657), who also discovered blood circulation and is considered one of the first great embryologists of the modern world (Mettler, 1947; Singer-Underwood, 1962; Westfall, 1987).

Harvey, in his embryology book titled 'Exercitationes De Generatione Animalium,' published in 1651 during his later years, determined that the first product of pregnancy is always a type of egg. He attempted to prove that viviparous animals also hatch from eggs and expressed this view with the famous maxim 'ex ovo omnia' (every living thing is born from an egg) (Hunter, 1931; Erk, 1978; Westfall, 1987; Theodorides, 1993). Continuing Fabricius' work, Harvey also studied the blastoderm, maturation, and the origin of blastocysts, using magnifying glasses/lenses during his work (Wolf, 1950; Dunlop-Williams, 1996). However, Harvey did not fully understand the ovum, mistaking the larva or pupa in insects and the membranes or chorion in mammals for the small embryo. His studies on deer led him to propose the view that the offspring originated solely from the female seed, with the male merely serving to facilitate its formation, like a magnet or a stimulant.

Embryological Theories

In the second half of the seventeenth century, since the ovum had not yet been discovered, Harvey is recognised as the founder of the 'ovist theory' (ovism), a theory stating that the embryo originates solely from the female animal (Erk, 1978; Westfall, 1987; Theodorides, 1993). However, Harvey also appears to have accepted the theory of 'spontaneous generation' for such creatures, as the eggs of insects, being very small creatures, are too small to be seen. Harvey also studied blood circulation in foetuses, demonstrated that the mother's blood provides nourishment for the foetus, and emphasised the similarities between the blood circulation of adult fish and foetuses (Needham, 1934; Erk, 1978). Harvey is one of the proponents of the 'epigenesis' (sequential formation) theory in embryology. According to this theory, the 'embryo' (foetus) is formed by the sequential addition of developing segments (Lyons-Petrucelli, 1987; Theodorides, 1993).

With the development of the microscope, from the first half of the 17th century onwards, old views gradually gave way to new ones (Petorak, 1988). Antony Van Leeuwenhoek (1632-1723) first observed human and animal spermatozoa under a microscope in 1677-1678 and illustrated them. As a result, the 'animalculist theory' began to emerge in opposition to Harvey's ovist theory. Contrary to the ovists, the animalculists argued that offspring were formed solely by male seed (Wolf, 1950; Westfall, 1987; Theodorides, 1993). Louis van Hamm, in 1677, proposed that the egg, which was immobile and therefore considered lifeless, was merely a storehouse of nutrients (Kayalı, 1989).

Another Dutchman, Niklaas Hartsoeker (1656-1725), published a small work showing drawings of male spermatozoa he observed under the microscope after Leeuwenhoek (Lyons-Petrucelli, 1987). Another Dutchman working in the field of embryology, Jan Swammerdam (1637-1687), examined the eggs of various animals (lice, ants, butterflies, frogs). As a result of these studies, he adopted the theory of 'preformation'. According to this theory, there is a very small embryo inside the egg, and this embryo contains the entire being of the animal in miniature form and gradually emerges by growing and developing from the membranes surrounding it. Supporters of the preformation theory also oppose the theory of epigenesis proposed by Harvey (Lyons-Petrucelli, 1987; Theodorides, 1993).

As can be seen, scientists living at the end of the 18th century were divided into two camps: those who accepted that the embryo underwent a preformation within the egg, known as 'preformation' or 'epigenesis', and those who attributed the fundamental role in the development of the organism to the egg or sperm, known as "ovists" or 'animalculists'. (Bernal, 1976; Lyons-Petrucelli, 1987; Theodorides, 1993).

New Developments in Embryology

Perhaps the greatest embryologist of the century, Marcello Malpighi (1628-1694), developed the technique of peeling the membrane of a newly laid egg and spreading it on glass, thereby enabling the use of the microscope in embryological studies (Westfall, 1987). With the aid of a simple microscope, he was able to see details that Harvey could not and made observations on reproduction, particularly in chickens and insects (Mettler, 1947; Theodorides, 1993). In his work, he defended the view that all animals are produced from eggs, based on the identification and development of the chicken egg. Malpighi's embryological study, published in 1666 under the title 'De formatione pulli in ovo', is of great importance (Mettler, 1947).

Thomas Wharton (1610–1673) was the first to describe the 'Wharton's jelly,' a loose embryonic connective tissue located in the umbilical region, which bears his name. Meanwhile, the Danish anatomist N. Stenon (1638–1686) conducted studies on the ovum in mammals and fish. while Dutchman Regnier de Graff (1641-1673) described the 'Graffian follicle' and the 'corpus luteum' in rabbits, dogs, cattle and human ovaries in 1672, and demonstrated the spermatic vessels using mercury injection. De Graff did not oppose Aristotle's views on reproduction, but stated that the embryo was solely a male product and that the mother had no function beyond nourishment and protection (Mettler, 1947; Wolf, 1950; Westfall, 1987; Theodorides, 1993). Furthermore, Italian Francesco Redi (1618-1676) attempted to disprove the theory of spontaneous generation through his experiments, which was one of the most significant developments of the century (Uzluk, 1959; Westfall, 1987; Sari, 1994). Nevertheless, by the mid-17th century, the problem of fertilisation and embryonic development was still far from being resolved (Theodorides, 1993).

The Scottish anatomist Alexander Monro (1687–1767) studied the uterus, the membranes surrounding the foetus, foetal circulation, the cotiledon and the allantois in cattle and in various animal species; his son, the anatomist Alexander Monro –secundus– (1733-1817), demonstrated that there is no relationship between foetal blood and maternal blood in mares and cows in the placenta. One of the most famous comparative anatomists, physician, and surgeon John Hunter (1728-1793), conducted studies on freemartinism, oestrus in animals, unilateral ovariectomy in young animals, and the structure of the placenta. He laid the foundations of placental anatomy by demonstrating that the maternal and foetal circulations are independent of each other (Mettler, 1947; Erk, 1978). Father Lazzaro Spallanzani (1729-1799), who clearly rejected the theory of spontaneous generation through his experiments, performed artificial insemination in frogs for the first time in 1777 and drew attention to the necessity of contact between sperm and egg for fertilisation (Erk, 1978; Theodorides, 1993). For approximately two hundred years, fierce debates took place between supporters of the preformation and epigenesis theories

(Wolf, 1950; Bernal, 1976; Kayalı, 1989; Theodorides, 1993).

However, the embryological studies of the German scientist Caspar-Friedrich Wolf (1733-1794) held an important place in the middle of the century. Wolf published his fundamental scientific observations in his works 'Theoria Generationis' in 1759 and 'De Formatione Intestin' in 1768. In these works, he demonstrated that organs are not preformed but gradually take shape during the formation of the embryo, providing strong support for the theory of epigenesis. He also studied the development of the intestines in chicks (Needham, 1934; Erk, 1978). The physiologist Albrecht von Haller (1708-1777), although initially accepting the theory of epigenesis, vehemently opposed Wolf's work, believing that his studies around 1760 proved that the chick embryo was preformed within the egg. He conducted original studies on the growth rate of the embryo, demonstrating that it grows at an incredible speed in the uterus and arguing that no organ can develop before another, but that they all take shape simultaneously (Needham, 1934).

The renowned Czech scientist Johannes Pürkinje (1787–1869) published a study in 1837 proposing that the animal organism consists of three primary forms: liquid, granular, and fibrous. He also demonstrated the structure of the vesicula germinativa in the embryo (Mettler, 1947; Dunlop-Williams, 1996). In the early nineteenth century, Swiss physician Jean-Louis Prevost (1790-1850) and French chemist Jean-Baptiste Dumas (1800-1884) conducted important research on fertilisation. In their work, building on Spallanzani's discoveries, they established the relationship between the presence of spermatozoa in seminal fluid and fertilisation capacity. The two scientists proposed that spermatozoa entered the egg and formed certain organs (such as the nervous system), while other organs originated from the egg and the egg membrane (Theodorides, 1993).

The German biologist Carl Ernst von Baer (1792–1876) first described and identified the egg cell within the tertiary follicle in dog ovaries in 1827. Furthermore, in his work published in 1828, he laid the foundation for knowledge about embryonic germ layers. For these reasons, von Baer is recognised as the founder of modern embryology. The embryonic germ layers mentioned by Baer were classified by Robert Remak (1815-1865) in 1845 according to their embryonic origins and named ectoderm (outer), mesoderm (middle) and endoderm (inner) (Dampier, 1957; Lyons-Petrucelli, 1987; Petorak, 1988; Theodorides, 1993). Physiologist Johannes Müller (1801-1858) also conducted numerous studies in the field of embryology and discovered the 'Müllerian duct,' named after him (Uzluk, 1959; Erdemir, 1994).

Rudolf Virchow (1821–1892) explained that all vital events and disease symptoms occur in the cells that make up the body, and that cells are the common building blocks of all living organisms. It was then understood that although both the ovum and the spermatozoon differ from other cells in shape and function, they are still cells. With

Oscar Hertwig's 1875 discovery that the spermatozoon enters the egg, the event of 'fertilisation' has been accepted as the beginning of life. Hertwig fully defined and explained this by observing the fertilisation of female and male germ cells for the formation of living organisms (Lyons-Petrucelli, 1987; Theodorides, 1993). In his work between 1883 and 1887, Belgian biologist E. van Beneden demonstrated that the egg and spermatozoon contain equal numbers of chromosomes and carry half the number of chromosomes of the germ cells from which they originate (Theodorides, 1993). The most important work of anatomy professor Wilhelm His was in embryology, and his first article on tissue layers and body cavities was published in 1865. This new classification of tissues became standard in embryology. He focused on structures originating from the mesoderm and conducted research on chick embryology in 1868. He completed his most important work, 'Anatomie Mensclier Embryonen,' in 1885, becoming the first scientist to work on a complete human embryo. (Mettler, 1947). As a result of his research, Walter Fleming reported in 1882 that the embryo grows, organs develop, and tissues can be renewed with the help of the cell division mechanism (Lyons-Petrucelli, 1987).

Modern Embryology

On the one hand, the cellular structure of gametes has been determined; on the other hand, cell theory has made it possible to definitively link all the formation processes of living organisms to divisions, transformations, or the displacement of cells. These new ideas have also influenced embryology (Theodorides, 1993). Meanwhile, the first histology textbook, written by Albert von Kölliker (1817-1905), also covered embryonic development in light of the new cell theory (Lyons-Petrucelli, 1987).

Following the definition of fertilisation, the morphological examination of the embryo continued throughout the 19th century and continues today. Although the main features of this reality are known, there are still many important points that need to be clarified today (Kayalı, 1989). A. Fischel first used vital staining in embryology research in 1903, while W. Wogt, in 1925, used vital stains to mark sections of the egg cell and showed where the cells that would develop from the blastomeres formed as a result of the 'segmentation' event would later migrate (Erbengi, 1988; Petorak, 1988). On the other hand, zoologist Hans Spemann (1869-1941) and his colleagues initiated experimental embryology studies.

Recently, with the understanding of the importance of DNA in reproduction and development, developmental events have also been approached from a molecular biology perspective, changing researchers' perspective on developmental events. New types of microscopes developed during this process have further strengthened the scientific foundations of this change. (Petorak, 1988). The importance of embryology has gained even more significance today, particularly with the proliferation of techniques such as

IVF, in vitro fertilisation, and cloning. In this way, embryology has begun to transform from a basic science into a discipline that is closer to clinical sciences and more applied.

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Green Chemistry and Ionic Liquids, an Alternative to Classical Solvents

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Introduction

Green chemistry applies core chemical principles to address worldwide challenges, including climate change, energy efficiency, sustainable agriculture, and resource depletion by engineering products and processes that avoid generating or utilizing hazardous materials (Poole et al., 1989). Therefore, it is an indispensable tool for sustainable development. Given current global conditions, it has become vital for chemists to integrate considerations related to human health and environmental sustainability into every aspect of their professional work. (Huddleston et al., 1998). When we look at the 150-year history of chemistry, green chemistry is a comparatively recent concept (Chiappe & Pieraccini, 2005). This movement began in the 1990s with the pollution prevention initiative, which called upon industry to reduce or eliminate pollution at its source rather than clean it up afterward (Aki et al., 2004; Jian, 2010). The U.S. Environmental Protection Agency (EPA) defined several environmental pollution prevention approaches, including inventory control, process control, in-process recycling, domestic changes, and green chemistry itself (Reyna-González et al., 2012).

Environmental pollution has become a critical global concern in today's world (Welton, 1999). Hydrometallurgical methods, which play a significant role in metal extraction from primary and secondary sources, are seeking highly efficient and environmentally friendly solvents other than traditional solvents. Ionic liquids, globally recognized as "green solvents," are emerging as a new type of substance that is beginning to replace traditional solvents (Zhang et al., 2009).

Green Solvents

The use of environmentally friendly solvents is an important option when producing new chemicals, and the use of water as a solvent in chemical reactions is an active area of research.

- Ionic Liquids
- Fluorinated Solvents
- Supercritical Fluids

Ionic liquids

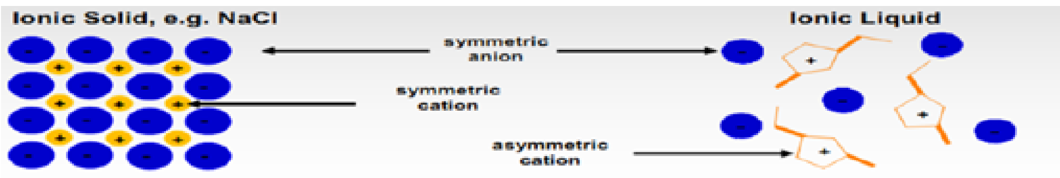
The general properties of ionic liquids are explained, and a literature analysis is provided to understand their usability. Considering the environmental and health concerns of today's world, problems such as the high number of solvents used, high energy and acid consumption, the need to recycle or dispose of waste solvents, and the potential for corrosion have led to the search for alternative solvents. Ionic liquids, with their outstanding properties and synthesizability, constitute a key element of this search (Shukla & Saha, 2013).

Various terms have been used to describe liquid salts such as fused salts, room-temperature ionic liquids, anhydrous ionic liquids, designer solvents, molten salts, liquid organic salts, room-temperature molten salts, and low-temperature molten salts have all been used to describe liquid salts, but ultimately, they all fall under the general concept of ionic liquids.

Ionic liquids, like common table salt (NaCl), consist of an anion–cation pair. However, unlike NaCl, where both ions are simple atomic species, in ionic liquids the ions are molecular and asymmetric in structure (Nockemann et al., 2008; Nockemann et al., 2006). **(Figure 1)**. Because of this asymmetry, the ions cannot easily pack into a crystalline structure, resulting in lower melting points. While conventional solvents such as acetone, dichloromethane, and water have molecular structures, ionic liquids are polar solvents composed of weakly bound positive and negative ions. Therefore, they are good solvents for a wide range of inorganic and organic compounds (halides BF_4^-, PF_6^-, ClO_4^-, CF_3COO^- $CF_3SO_3^-$ vd.). Ionic liquids (ILs) are defined as salt systems incorporating organic cations, anions, or both, distinguished by melting points below 100°C—significantly lower than those of conventional inorganic salts. Those maintaining a liquid state at ambient conditions are termed Room-Temperature Ionic Liquids (RTILs). Structurally, these salts arise from the weak association between bulky organic cations, such as 1-alkyl-3-alkylimidazolium or 1-alkylpyridinium, and various organic or inorganic anions. The anionic counterparts can be inorganic species, such as hexafluorophosphate (PF_6^-), tetrafluoroborate (BF_4^-), chloroaluminate ($AlCl_4^-$), chloride (Cl^-), or organic anions such as acetate (CH_3COO^-).

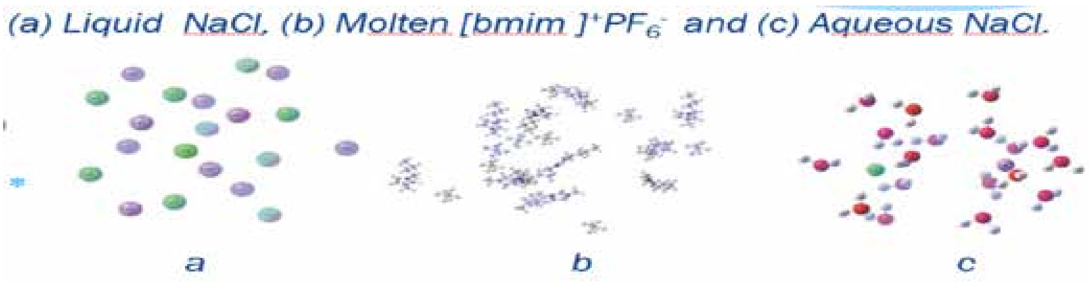
Figure 1

Ionic liquids, like common table salt (NaCl), consist of an anion–cation pair.



When the constituent ions of an ionic liquid are relatively bulky, the resulting charge-to-size ratio is effectively diminished. This leads to low lattice energy, weaker electrostatic interactions, and consequently lower melting points. However, the presence of large ions also results in high viscosity, and therefore the conductivity of the medium tends to be lower **(Figure 2)**.

Figure 2
Liquid, ionic liquids (ILs) and aqueous



Discovery and History

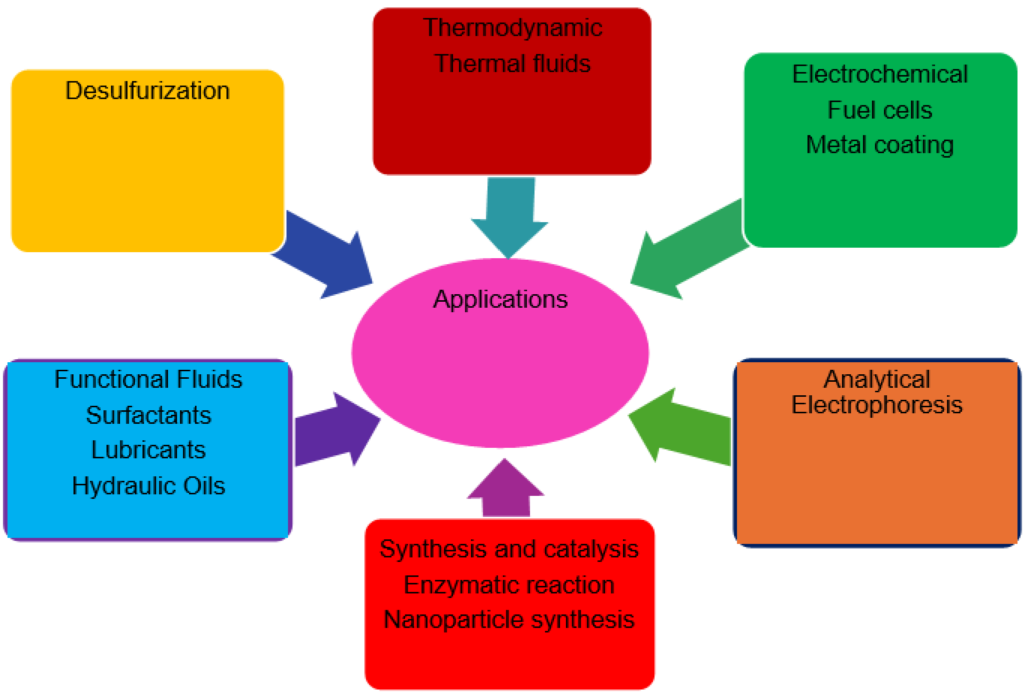
The historical origins of ionic liquids go back to 1914, marked by Paul Walden's identification of ethylammonium nitrate, which represented a pivotal moment in the chemistry of solvents. In 1967, Swain advanced the field by employing tetra-N-hexylammonium benzoate as a solvent in an electrochemical reaction, demonstrating the potential of ionic liquids in electrochemical applications. A breakthrough occurred in 1970 when Oster, Young, and colleagues synthesized the first ionic liquid that was stable at room temperature, greatly expanding practical usage possibilities. In the 1980s, Seddon and his research group pioneered the use of ionic liquids as catalysts in various solvent systems, further showcasing their versatility. By 1992, Wilkes synthesized a new class of ammonium-based salts and introduced them as innovative solvents and ionic liquids, opening the door to modern applications and establishing ionic liquids as important materials in green chemistry and advanced technologies.

Ionic liquids have found extensive application across a wide range of scientific and industrial fields due to their unique physicochemical properties. They serve as highly effective solvents and catalytic assistants in numerous chemical reactions, enhancing reaction efficiency and selectivity (Kumar, 2005). Their broad electrochemical stability has also enabled their use in battery technologies, where they offer improved safety and performance. In biotechnology, ionic liquids act as support materials for enzyme immobilization, providing stable and versatile environments for biocatalytic processes (Hernández-Fernández et al., 2010). Their excellent solvating ability makes them valuable solvents in extraction processes, enabling efficient separation and purification of target compounds (González et al., 2018). Additionally, ionic liquids function as advanced lubricants with high thermal stability and low volatility, improving tribological performance (Bermúdez et al., 2009). They are also used as template materials in the synthesis of nanomaterials, allowing controlled formation of nanostructures (Namboodiri & Varma, 2002). Within the scope of analytical chemistry, ionic liquids act as crucial elements for stationary phases in gas chromatography (Armstrong et al., 1999) and serve as additives in liquid chromatography mobile phases to improve separation performance (Xiaohua et al., 2004). Furthermore, they serve as moving electrolytes in capillary electrophoresis, improving ion transport and analytical resolution. These diverse applications highlight the versatility and growing importance of ionic liquids in modern science and technology.

Properties of Ionic Liquids

These fluids exhibit a variety of beneficial characteristics, such as negligible vapor pressure, significant viscosity, a broad temperature range for the liquid state, and the capacity to solvate both organic and inorganic substances, alongside high thermal and oxidative stability. Their negligible volatility, easy removal from reaction media, resistance to high temperatures, and ability to leave no residue further enhance their usefulness. In addition, their high polarity, low toxicity, non-flammable nature, reusability, catalytic activity, hydrogen-bonding capacity, Lewis's acidity, and immiscibility with many organic solvents expand their application potential. Altogether, these features make ionic liquids superior to conventional solvents and justify their classification as "Green Chemistry Materials" due to their environmentally friendly characteristics **(Figure 3)**.

Figure 3
Application areas of ionic liquid



Binary Ionic Liquids (Equilibrium)

Room-temperature ionic liquids based on halogens- and alkylhalogenoaluminate(III) species represent one of the most extensively investigated classes in literature. However, their sensitivity to moisture and water limits their practical applications. The first member of this class was obtained by mixing 1-alkylpyridinium bromide with $AlCl_3$. Similarly, mixtures of 1-ethyl-3-methylimidazolium chloride ([emim]Cl) and $AlCl_3$ were found to be liquid, which led to extensive studies on imidazolium-based salts. In addition to chloroaluminate systems, [emim]Br–$AlBr_3$ ionic liquids were also prepared. Among these, 1-butyl-3-methylimidazolium ($[bmim]^+$) salts are the most frequently used. Typical equilibrium species found in binary systems include.

Simple Salts (Single Anion and Cation)

The earliest example of an ionic salt is ethylammonium nitrate $[EtNH_3][NO_3]$, which also represents a simple ionic liquid. There exists a vast number of possible anion-cation combinations for synthesizing ionic liquids. The most used cations include 1-alkylpyridinium/1-alkylimidazolium cations.

Tetraalkylphosphonium/Tetraalkylammoniums used liquids and are stable toward both air and moisture, and some are even hydrophobic. Although they are more resistant to hydrolysis than halogenoaluminate(III) ionic liquids, many ammonium and imidazolium salts are hygroscopic, absorbing moisture even when their containers are opened. Modifying the structure of the cation or anion, compounds with diverse physical and chemical properties can be obtained. Because of this tunability, ionic liquids are also referred to as “designer solvents”. It is estimated that millions of anion cation combinations could theoretically be designed using this approach.

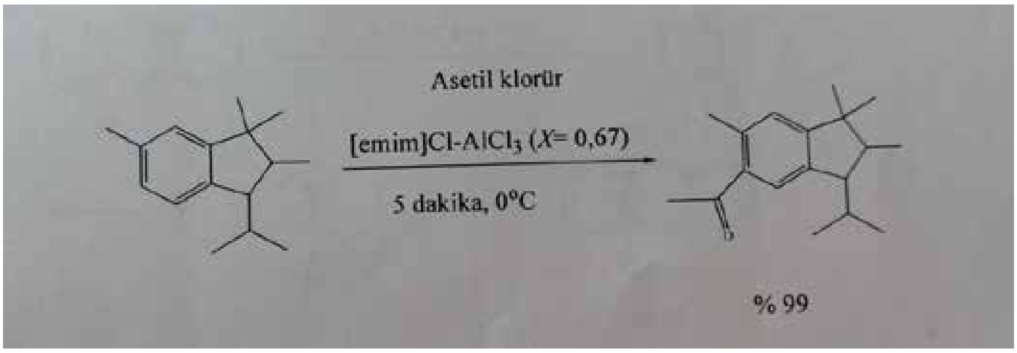
Reactions of Ionic Liquids

Friedel–Crafts Reactions

Friedel-Crafts reactions frequently employ chloroaluminate(III) ionic liquids. Due to their ability to dissolve a diverse array of aromatic compounds, these liquids serve as a superior medium for such reactions. To perform a Friedel–Crafts reaction in ionic liquids, an electrophilic species must first be generated within the medium. Many commercially important fragrance intermediates can be synthesized through Friedel–Crafts acylation reactions conducted in ionic liquids. For instance, Triazolide (5-acetyl-1,1,2,6-tetramethyl-3-isopropylindane) can be synthesized with high yield using [emim] Cl–$AlCl_3$ ($X = 0.67$) ionic liquid as the medium **(Figure 4)**.

Figure 4

Triazolide (5-acetyl-1,1,2,6-tetramethyl-3-isopropylindane) can be synthesized with high yield using [emim]Cl–AlCl₃ (X = 0.67) ionic liquid as the medium

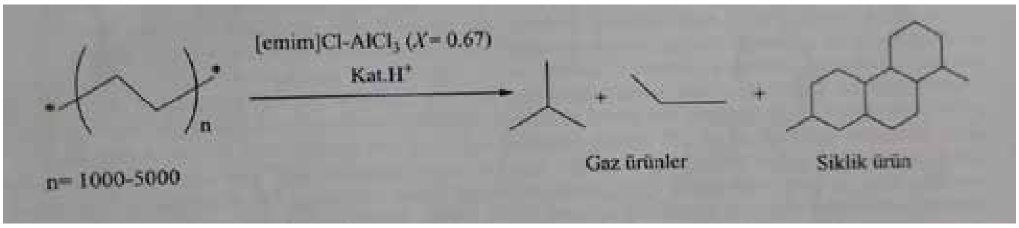


Cracking (Decomposition) Reactions

Decomposition, or cracking reactions, proceed readily within acidic chloroaluminate(III) ionic liquids, with the depolymerization of polyethylene serving as a prime example. When polyethylene is decomposed at elevated temperatures, it converts into volatile alkanes (such as propane, butane, pentane) and cyclic alkanes. While classical catalytic cracking requires very high temperatures (300–1000 °C), the same reactions can proceed in ionic liquids at temperatures as low as 90 °C, making them far more energy-efficient **(Figure 5)**.

Figure 5

Acidic chloroaluminate(III) ionic liquids readily facilitate cracking reactions.

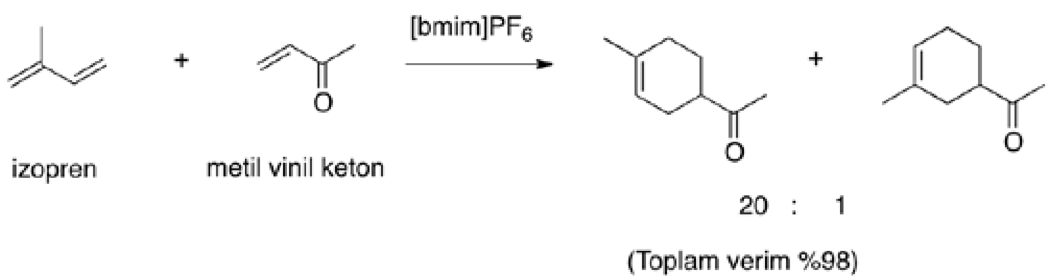


Diels–Alder Reactions

The Diels–Alder reaction, used to synthesize cyclic compounds, can also be carried out in ionic liquids as an alternative to water-based solvent systems. It has been observed that, when mixed with nonpolar organic solvents, the reaction rate increases significantly **(Figure 6)**.

Figure 6

The Diels–Alder reaction

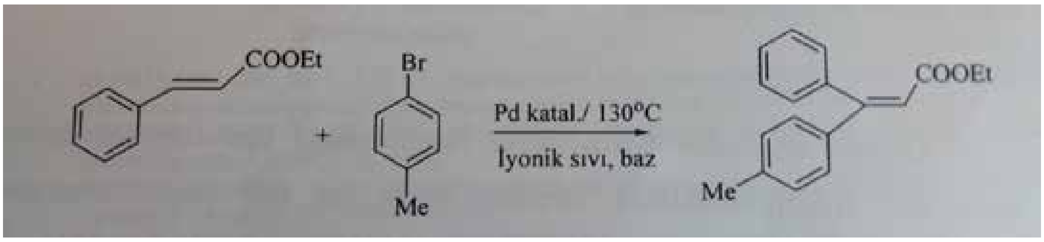


Heck Reactions

The Heck reaction involves palladium(0)-catalyzed coupling between alkenes and aryl halides. In ionic liquids, the catalyst dissolves effectively, and the product can be easily extracted using a nonpolar organic solvent. When water is added, a three-phase system forms, allowing the resulting salts to move into the aqueous phase. The formation of a palladium–carbene complex from the imidazolium cation in [bmim][Br] ionic liquid plays a crucial catalytic role. Studies have shown that iodo or bromobenzene with electron-withdrawing groups undergo Heck coupling reactions with styrene or acrylates more efficiently in [bmim][Br], due to the higher activity of the imidazolium bromide-derived carbene complex **(Figure 7)**.

Figure 7

The Heck reaction involves palladium(0) catalyzed coupling between alkenes and aryl halides. In ionic liquids



Applications for Ionic Liquids

Use of Ionic Liquids in Fuel Cells

With the increasing global demand for energy, research on clean and renewable energy sources has gained great importance. At the same time, studies focusing on the methods of energy utilization have rapidly expanded. Fuel cells are distinguished among alternative energy technologies by their exceptional efficiency, cost-effectiveness, quiet operation, and environmental compatibility. They are therefore expected to be widely adopted in the future. In Polymer Electrolyte Membrane (PEM) fuel cells, energy production performance largely depends on ion (proton) transport through the polymer electrolyte membrane. Ensuring the long-term stability of PEM fuel cells under high-temperature conditions is a critical requirement. Studies have shown that polyimide–ionic liquid composite membranes, both acid-doped and undoped, exhibit superior mechanical and thermal properties compared to conventional membranes used in the literature.

Chemical behavior of polynuclear transition-metal complexes in ionic liquid environments

Ionic liquids incorporating transition metals are viewed as promising hybrid materials that merge the intrinsic characteristics of ionic liquids with specific magnetic, optical, or catalytic functionalities. Various traditional methodologies exist for the synthesis of polynuclear transition-metal complexes. Historically, these compounds were primarily produced through high-temperature techniques, such as melt crystallization or chemical vapor transport [22–31]. Alternatively, synthesis involved processing precursors within various solvent environments, including inorganic media (like aqueous HCl or water) and organic solvents ranging from non-polar types (e.g., benzene, ether) to polar ones (e.g., acetonitrile, dichloromethane) **(Figures 8, 9, 10, 11).**

Figure 8

Binuclear complexes in ionic liquids

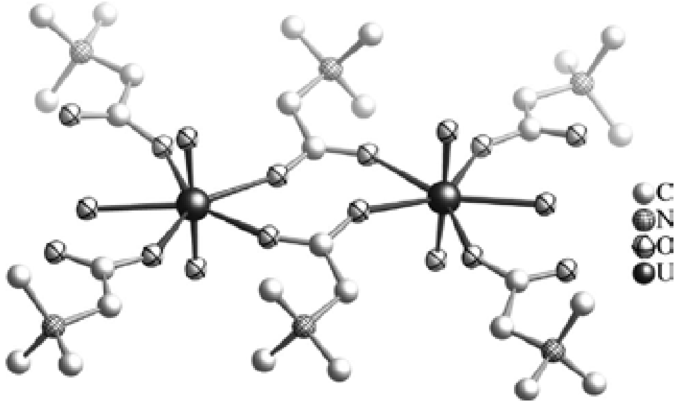


Figure 9

Trinuclear complexes in ionic liquids

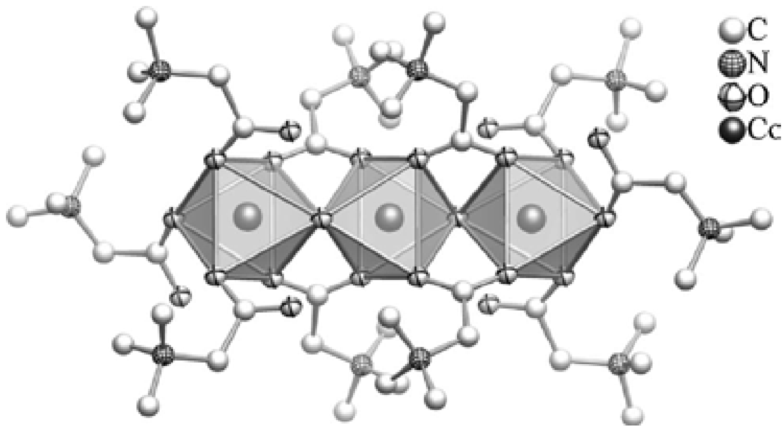


Figure 10

Tetranuclear complexes in ionic liquids

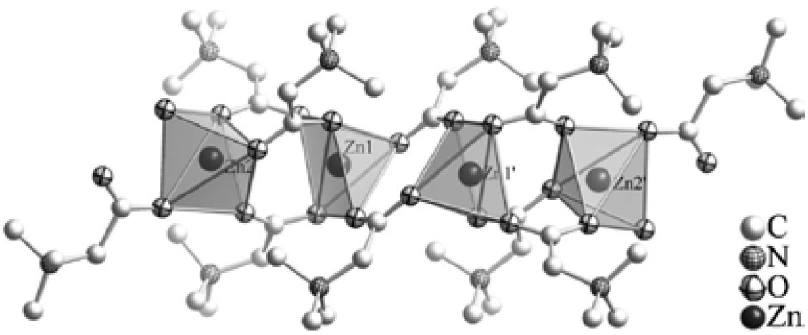
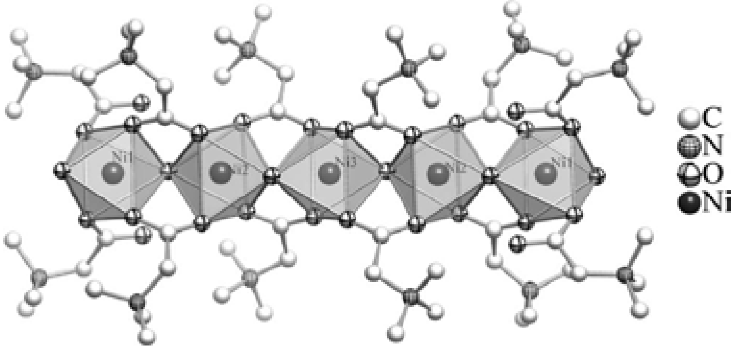


Figure 11

Pentanuclear complexes in ionic liquids

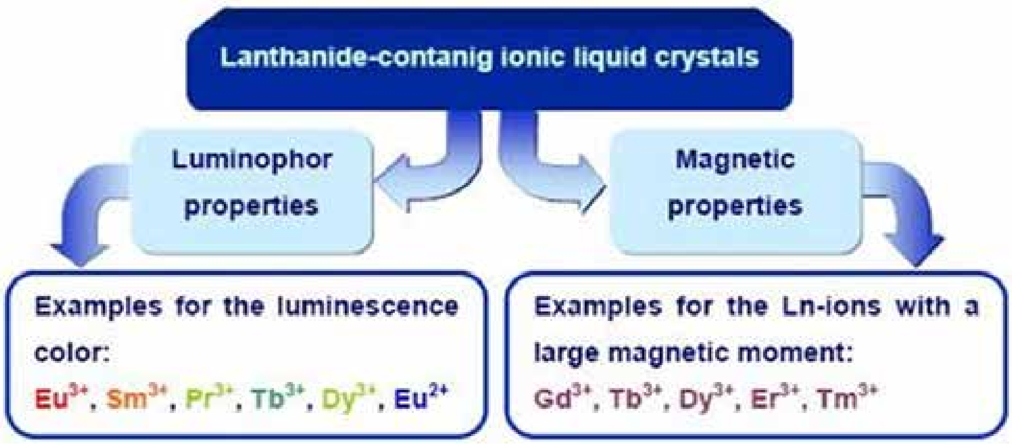


Magnetic Ionic Liquids

Magnetic Ionic Liquids (MILs) represent a specialized category of ionic fluids designed to possess magnetic characteristics by integrating paramagnetic or ferromagnetic ions or complexes into their structure **(Figure 12)**. While maintaining the inherent benefits of ionic liquids, such as negligible volatility, thermal endurance, and adjustable physicochemical properties, these advanced materials also possess the unique ability to respond to external magnetic fields. This added functionality allows MILs to be applied in advanced separation processes, targeted extraction, magnetic switching, catalysis, sensing technologies, and smart material design, making them highly promising for next-generation green and multifunctional chemical systems.

Figure 12

The Effect of Magnetism on Ionic Liquids



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Current Physiotherapy-Focused Approaches to Sustainable Exercise

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Introduction

The Purpose Of Sustainable Exercise Within Physiotherapy Practice

Physiotherapy stands as a key discipline in the comprehensive management of a wide array of conditions, encompassing musculoskeletal disorders, neurological diseases, and chronic pain states (O'Halloran et al., 2014). Despite established protocols for acute phase management, the discipline faces a persistent, highly challenging, and economically consequential hurdle: securing long-term adherence (adherence) to the prescribed exercise regimen and ensuring the sustained maintenance of functional gains after acute symptoms have subsided and direct clinical oversight has concluded.

This chapter's primary objective is to present a comprehensive, evidence-based Biopsychosocial (BPS) model designed to mitigate the prevailing high rates of exercise non-adherence and program dropout within physiotherapy. This proposed model systematically harmonizes biomechanical sensitivity with established behavioral sciences, including Cognitive Behavioral Therapy (CBT) and Motivational Interviewing (MI), alongside strategic technological integration. Successful long-term clinical outcomes are fundamentally dependent on a professional paradigm shift where the physiotherapist's role evolves dramatically from being solely an "exercise prescriber" to functioning as a "behavioral coach" who actively nurtures and supports the patient's capacity for autonomy and self-management (Morley et al., 1999).

The Concept of Exercise Sustainability in the Physiotherapy Process

Exercise sustainability is conceptually defined as the patient's active, enduring commitment to continuing rehabilitation goals, maintaining independent functional capacity, and proactively preventing secondary injuries long after the therapeutic guidance of the physiotherapist has ceased (O'Halloran et al., 2014). This definition implies a commitment beyond the mere mechanical execution of assigned exercises. Crucially, it necessitates the individual's successful adaptation of acquired skills and knowledge into the complexities of their daily life and the effective utilization of self-management skills to proactively handle potential setbacks, such as pain recurrence or the inevitable decline in motivation (Morley et al., 1999).

Dropout Rates and Clinical Outcomes

The correlation between high patient participation and adherence with superior clinical outcomes is direct and well-documented. However, adherence rates for unsupervised home exercise programs (HEPs) remain distressingly low, rendering high dropout rates a significant concern for the clinical utility and cost-effectiveness of physiotherapy interventions (O'Halloran et al., 2014).

Quantitative meta-analytic evidence confirms specific risks associated with exercise dosing: for patients with Type 2 Diabetes Mellitus (T2DM), high-intensity exercise training protocols carried a notably higher risk of program abandonment compared to moderate-intensity protocols, quantified by an Odds Ratio (OR) of 1.81 ($p=0.01$) (Ríos-Rodríguez et al., 2019). This finding suggests that even if a high-intensity protocol is biologically optimized for maximal physiological efficiency, its potential efficacy can be profoundly undermined by the psychological barrier created by the patient's perceived difficulty or effort required. Consequently, the sustained success of a prescription requires balancing biological potential with feasibility and the patient's psychological compliance, rather than aiming for maximal tolerable intensity alone.

Furthermore, the choice of exercise modality significantly influences long-term adherence rates. A systematic review focused on pediatric oncological rehabilitation demonstrated that dropout rates in programs featuring more enjoyable modalities—specifically strength training or exergaming (8.6%–8.7%)—were nearly halved compared to traditional multi-component programs (18.4%) (Fernández-Álvarez et al., 2024). This highlights the critical role of hedonic and contextual factors (such as enjoyment and social engagement) in promoting sustained behavioral effort. The implication is clear: incorporating elements that foster intrinsic desire, or joy, into the exercise design is essential for long-term behavioral maintenance, shifting the therapeutic focus from mandatory compliance to self-selected sustained participation.

Physiological And Biomechanical Foundations Of Sustainable Exercise

Breaking the Pain-Kinesiophobia Cycle

Kinesiophobia (Fear of Movement) and the Fear-Avoidance Model (FA Model)

Kinesiophobia is medically defined as an irrational, excessive, and functionally debilitating fear directed toward movement or physical activity due to the anticipation of pain or re-injury (Vlaeyen et al., 1995). The Fear-Avoidance (FA) Model posits that when an individual interprets a painful event as fundamentally threatening, this interpretation precipitates catastrophizing cognitions—the exaggerated and negative forecast that any movement will inevitably lead to greater pain and harm (Vlaeyen & Linton, 2000). This maladaptive perceptual process sustains a vicious cycle of disuse, chronic disability, and avoidance behavior (Vlaeyen & Linton, 2000). Research indicates that the mediatory role of pain-related fear tends to be more potent and pronounced in older populations suffering from chronic pain.

Exposure-Based Approaches (Exposure Therapy)

Graded Exposure (GE) therapy is a specialized Cognitive Behavioral Therapy (CBT) technique specifically designed to address kinesiophobia (Vlaeyen et al., 1995). The treatment progresses through systematic exposure to feared activities, which are initially organized according to a patient-specific fear hierarchy (Vlaeyen & Linton, 2000). The therapeutic objective is the attenuation of pain perception through the repeated, experiential proof that movement, when performed under controlled conditions, is safe (Vlaeyen et al., 1995).

GE is commonly contrasted with Graded Activity (GA), which aims for a general increase in activity levels based on pre-set quotas (Vlaeyen et al., 1995). Comparative analyses of Randomized Controlled Trials (RCTs) indicate that there are no statistically significant differences in outcomes concerning disability or pain intensity between GE and GA at either post-treatment or six-month follow-up periods (Wang et al., 2022). This finding suggests that the core mechanism of therapeutic change may not be narrowly restricted to the extinction of a specific phobia, but rather involves the broader therapeutic achievement of re-establishing general movement confidence and increasing functional tolerance. Consequently, successful, symptom-guided, progressive loading may fulfill the necessary behavioral and cognitive restructuring requirements without the strict hierarchical protocols traditionally associated with specialized phobia treatments.

Individual Loading Capacity and Optimal Dosage

The physiological foundation for long-term sustainable exercise is the principle of optimal loading. This principle requires the clinician to prescribe the precise exercise stimulus that maximizes positive tissue adaptation while simultaneously minimizing the inherent risk of future injury (Wilson et al., 2021).

The prescription of exercise intensity, volume, and frequency must be acutely sensitive to the non-uniform and complex recovery kinetics of different musculoskeletal tissues (Gabbett & Oetter, 2025). For instance, muscle tissue incurring eccentric damage typically requires a resting period of 72 hours for full recovery following high-stress activities. Tendons exposed to high-tensile stretch-shortening cycles (SSC) require a 48-hour refractory period before they can safely absorb a similar loading dose. Conversely, bone cells rapidly desensitize to repetitive load, requiring only a short resting period of 4–8 hours before load reapplication to sustain optimal adaptation. In the context of multi-tissue injuries, the program's frequency must be conservatively adjusted to align with the regeneration time of the slowest healing tissue involved (Gabbett & Oetter, 2025). Neglecting these differential recovery rates—for example, by loading a tendon at a bone adaptation frequency—will inevitably lead to accelerated micro-trauma and subsequent pain relapse, which in turn reinforces avoidance behavior and leads to program abandonment.

Functional Movement Screening and Biomechanical Analysis

Biomechanical analysis, which includes monitoring the accumulation of stress and strain over time, constitutes the foundational element for individualizing exercise prescription and ensuring adherence to the optimal loading paradigm (Wilson et al., 2021). Clinically, the appropriate optimal loading dosage is primarily guided by monitoring symptoms. Optimal load is practically defined as the highest level of load that does not elicit symptoms either during the activity, immediately following, or on the subsequent day (Wilson et al., 2021). This strategy of symptom-guided loading is not only a physical safeguarding measure but also a critical psychological intervention. By engineering controlled experiences of pain-free success, it effectively dismantles the patient's catastrophic belief that movement is dangerous, thereby directly combating the Fear-Avoidance cycle (Vlaeyen & Linton, 2000). Biomechanical precision, therefore, functions as a powerful, experience-based mechanism for building foundational self-efficacy.

Patient-Centered Current Approaches

Self-Efficacy and Exercise Adherence

Self-Efficacy, defined as an individual's conviction in their capability to successfully execute necessary tasks 4, is widely recognized as the most reliable psychological predictor of long-term exercise sustainability (O'Halloran et al., 2014). A fundamental shift in the physiotherapist's core responsibility involves not merely instructing exercises, but actively cultivating the patient's capacity for self-management—the ability to independently govern their symptoms and their exercise regimen. This empowerment directly bolsters the patient's sense of internal control and self-efficacy (Morley et al., 1999).

Empirical evidence confirms that therapeutic programs incorporating behavioral interventions, such as Motivational Interviewing (MI), significantly increase not only overall compliance but also the self-efficacy levels of patients managing chronic conditions (O'Halloran et al., 2014). As articulated by Bandura's theory, the primary catalyst for self-efficacy is the mastery experience (Morley et al., 1999). Accordingly, goal setting must ensure that targets are realistic, achievable, and functionally congruent with the patient's expectations. The deliberate use of SMART goals (Specific, Measurable, Achievable, Relevant, Time-bound) enables patients to accumulate continuous, minor successes, thereby profoundly reinforcing their belief in their increasing physical capabilities. These controlled successes, established through optimal loading and graded exposure techniques, serve as a potent counter-mechanism against negative, kinesiophobia-derived beliefs (Morley et al., 1999).

Integration of Cognitive Behavioral Therapy (CBT) Principles

CBT provides a structured, highly evidence-based methodology that is utilized extensively in both pain management and the promotion of behavioral adherence within physiotherapy (George et al., 2007). The organized, systematic nature of the CBT process exhibits a high degree of compatibility with the standard examination and evaluation procedures used by physiotherapists, positioning them optimally to deliver CBT-informed education and intervention.

Targeting Catastrophizing and Modifying Negative Beliefs

Catastrophizing is defined as a cognitive bias characterized by excessive rumination on painful experiences, an exaggeration of anticipated negative outcomes, and intense feelings of helplessness.141 Elevated levels of catastrophizing actively diminish resilient behaviors, accelerating and strengthening the avoidance cycle. CBT directly addresses this through cognitive restructuring (CR), a technique that helps patients identify ingrained, automatic errors in their exercise-related thoughts and systematically replace them with more realistic and balanced cognitions (George et al., 2007). Meta-analyses consistently demonstrate that cognitive restructuring maintains a robust and large effect size in diminishing the intensity of chronic pain (Pintea & Maier, 2024). Importantly, data suggests that even behavioral interventions rooted primarily in exercise, lacking explicit cognitive components, can still lead to a simultaneous reduction in pain catastrophizing alongside decreases in disability and pain intensity (George et al., 2007). This correlation implies that the successful act of moving safely and mastering a physical task provides a powerful, non-verbal cognitive intervention that empirically disproves the patient's catastrophic expectations.

Motivational Interviewing (Motivational Interviewing - MI)

Motivational Interviewing (MI) is a rigorously patient-centered communication style developed specifically to enhance the intrinsic motivation of individuals struggling with ambivalence toward behavior change.71 Physiotherapists leverage MI's core communication skills—known by the acronym OARS (Open-ended Questions,

Affirming, Reflective Listening, Summarizing)—to assist the patient in resolving their internal conflict (ambivalence) and eliciting change talk—statements reflecting the patient's own reasons for wanting to change (Zhou et al., 2024).
Meta-analyses confirm the strong quantitative efficacy of MI, reporting statistically significant positive effects on physical activity (Odds Ratio: 1.76) and general treatment adherence (OR: 1.38). Furthermore, MI-inclusive interventions have been associated with significant short-term gains in total physical activity (an average increase of 1,323 steps per day) and in participation in moderate-to-vigorous physical activity (an increase of 95 minutes per week) (Zhou et al., 2024). MI also provides substantial support for long-term exercise self-efficacy (Rous et al., 2019).

A critical observation regarding MI effectiveness is that despite strong initial effects, the behavioral improvements frequently do not maintain persistence beyond one year (Zhou et al., 2024). This temporal limitation emphasizes a crucial gap between the initiation of intrinsic motivation achieved during therapy and the need for structural support systems necessary to maintain that behavior long-term. This necessitates the integration of continuous environmental and technological supports.

Technology And Environmental Integration For Long-Term Adherence

Tele-Rehabilitation and Mobile Applications

Tele-rehabilitation serves as a critical structural solution for overcoming geographical barriers, enabling the maintenance of adherence to the Home Exercise Program (HEP) well into the post-rehabilitation phase (Wang et al., 2022). Virtual platforms and mobile applications are potent compliance boosters, offering features such as remote monitoring capabilities, exercise video libraries, and automated reminders (Wang et al., 2022).

For patients managing chronic diseases, the utilization of wearable devices provides real-time, patient-centered health data, significantly empowering them to make independent, informed decisions regarding self-management (Bérubé et al., 2024). In specialized fields such as cardiac rehabilitation, tele-rehabilitation programs incorporating real-time monitoring of biometric data (e.g., heart rate, respiration rate, and accelerometry) via chest-worn sensors have achieved outcomes that are either comparable or superior to those of traditional in-person rehabilitation models (Wang et al., 2022). These systems guarantee both the safety and efficacy of exercise outside of a supervised laboratory setting. A systematic review assessing tele-rehabilitation interventions concluded that approximately 50% of the included studies demonstrated a positive impact on pre-defined primary outcome measures (Wang et al., 2022).

Objective Feedback through Wearable Technologies

Wearable technologies, including activity trackers and biosensors, expand the clinical reach of physiotherapy by providing objective, real-time data to support the self-management of chronic conditions (Bérubé et al., 2024). While the overall impact of these devices on objective physiological metrics, such as body mass index (BMI) or quantifiable physical activity levels, has been mixed, approximately 83% of studies that employed subjective measures (e.g., patient experience or quality of life) reported positive effects (Wang et al., 2022).

This divergence between objective and subjective findings indicates that the primary clinical value of wearables is not merely in measuring compliance but in facilitating patient empowerment and behavioral/cognitive change through enhanced self-awareness (Wang et al., 2022). Therefore, clinicians should position these tools to patients as mechanisms for gaining control and supporting self-management, rather than simply as tools for compliance tracking, to maximize their adherence benefits. Looking forward, the integration of Artificial Intelligence (AI) and Machine Learning (ML) is expected to provide transformative predictive insights and highly personalized treatment algorithms within this technological framework (Wang et al., 2022).

Community and Social Support Systems

Individual-level interventions, however robust, are insufficient alone to guarantee long-term participation; they must be complemented by community and social support systems. Structured group exercise programs designed for chronic conditions are particularly effective, as they boost participation rates by establishing crucial social cohesion and external accountability (Fernández-Álvarez et al., 2024). The phenomenon of group members observing and acknowledging one another's achievements—known as vicarious experience—provides indirect reinforcement that strengthens individual self-efficacy and belief in their self-management capabilities (O'Halloran et al., 2014). This social context offers the necessary structural and persistent environment for motivation and reinforcement, effectively solving the critical retention problem observed with Motivational Interviewing interventions beyond the one-year mark (Zhou et al., 2024). Sustainable motivation must transition from being therapist-dependent to being peer-group supported.

Conclusion

Key Implications Specific to Physiotherapy

The successful attainment of sustainable exercise behaviors necessitates a sophisticated, integrated approach that seamlessly fuses contemporary biomedical and biomechanical knowledge with expertise in behavioral science.

The fundamental clinical implication for physiotherapy practice is the necessity of ensuring that exercise prescription is managed with absolute biomechanical precision. This requires strict adherence to the Optimal Loading Principle, which dictates that load advancement must be paced according to the regeneration kinetics of the slowest-recovering tissue (Gabbett & Oetter, 2025). Furthermore, loading must be guided by patient symptoms (pain-free progression) to generate the necessary safety experiences that effectively extinguish kinesiophobia (Wilson et al., 2021).

This sound physiological foundation must be substantially augmented by high-level behavioral coaching. This involves using Motivational Interviewing (MI) techniques to maximize adherence and self-efficacy (O'Halloran et al., 2014) , and systematically employing Cognitive Behavioral Therapy (CBT) principles, specifically cognitive restructuring, to target and modify maladaptive cognitions such as catastrophizing (Pintea & Maier, 2024; George et al., 2007).

Finally, the guarantee of long-term compliance is secured by external, continuous support systems: the objective and subjective data provided by wearable technologies (Bérubé et al., 2024) combined with the continuous remote monitoring and environmental support facilitated by tele-rehabilitation and dedicated community support groups (Wang et al., 2022).

Future Perspectives

Future clinical development and advanced research in exercise sustainability must strategically focus on enhancing the efficacy and persistence of current multi-modal approaches.

It is imperative that advanced research investigates the effectiveness of sustained reinforcement interventions—such as digital support systems or periodic 'booster sessions'—necessary to institutionalize and maintain the short-term behavioral gains achieved through Motivational Interviewing, addressing the problem of long-term retention (Zhou et al., 2024).

Furthermore, a crucial future direction involves the development of Artificial Intelligence (AI) supported algorithms. These sophisticated systems must be designed to integrate and analyze physiological, biomechanical, and psychological risk factors (e.g., kinesiophobia scores, adherence rates, tissue recovery kinetics). Such algorithms would possess the capability to predict patient dropout probability and deliver dynamically personalized, optimized exercise prescriptions (Wang et al., 2022).

In the biomechanical domain, definitive randomized controlled trials and advanced biomechanical analyses are still necessary to precisely determine and validate the physiological boundaries of optimal loading dosages for high-risk, slow-adapting tissues, including ligaments and sites prone to bone stress injuries.

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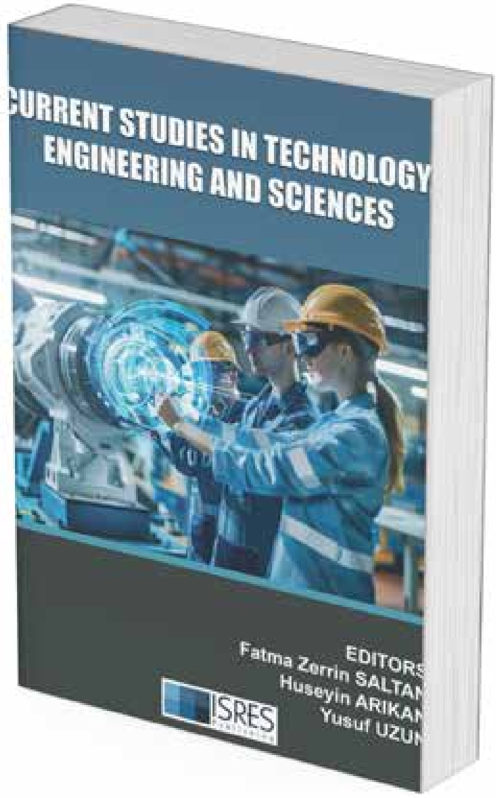

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